BEFORE THE HON'BLE NATIONAL GREEN TRIBUNAL

PRINCIPAL BENCH AT NEW DELHI

OBJECTION BY APPLICANT

In

ORIGINAL APPLICATION NO. 511 OF 2023

IN THE MATTER OF

Priyank Bharati ------**APPLICANT IN PERSON**

Versus

State of Uttar Pradesh through its Chief Secretary and others

-----**RESPONDENTS**

INDEX

Place : Meerut

Date : 09.10.2025

Bharati

Priyank Bharati

(Applicant In Person)

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Affidavit-cum-Objection by Applicant to the Report Submitted by the Chief Engineer (Ganga), Irrigation and Water Resources Department, Meerut, Government of Uttar Pradesh dated 11 July 2025

MOST RESPECTFULY SHOWETH;

I, Priyank Bharati R/O Jagriti Vihar Meerut-250004, UP hereby solemnly affirm and declare as under:

1. That the River (Budhi Ganga), which carries within its course the cherished legacy and historical reminiscence of the Mahabharata era, represents an invaluable element of India's natural and cultural heritage - a heritage which, regrettably, the institutions of independent India have failed to preserve and protect in accordance with their constitutional and statutory obligations.
2. That in compliance with the directions issued by the Hon'ble Tribunal, the Flood Plain of River Budhi Ganga has been demarcated by the Irrigation Department (as most of the data given by Irrigation

department itself to NIH) through the National Institute of Hydrology (NIH), Roorkee.

3. That the Applicant has repeatedly communicated through official emails requesting the KML files pertaining to the said demarcation; however, several essential files, including the alignment of the river along with its cross-sections, have not been furnished to the Applicant till date. The copy of the email is enclosed herewith and marked as **ANNEXURE 1**

4. That, according to the report page no 671, 672, 673, 678 and 680 the **identification of the origin point of River Budhi Ganga** has been **erroneously** determined, thereby rendering the entire delineation of its floodplain scientifically untenable and legally unsustainable. The Report stands vitiated ***ab initio***, as it is founded upon an incorrect and defective point of commencement.

5. That, according to the report contradictory statements are made regarding the number of river reaches (Pages 660 and 669)

On **page no. 660**, it is stated that:

> *"During the field visit by NIH team along with Irrigation and Water Resources Department, Govt. of U.P., it was also found that at present there are* ***four river*** *reaches."*

Whereas, on **page no. 669**, it is stated that:

> *"The Budhi Ganga River, a tributary, is having very less width and water flows mainly during the rainy season and joins the Ganga* ***River at 3 to 4 locations****"*

Both **statements are contradictory** in nature. The report is thus ambiguous even regarding the fundamental geomorphic characterization of the river. The Irrigation Department to ascertain the actual number and continuity of river reaches clearly reflects verification and lack of hydro-geomorphic clarity. It proves that till date, the concerned departments do not possess the actual delineation or verified stretches of River Budhi Ganga.

6. That on **page 659, point no. 7** of the report, it is stated that the three issues earlier faced by NIH, as mentioned in the previous affidavit dated 12.03.2025 (at page 627), have been rectified, and the details of such rectifications are provided on **page 660** of the report. There are some objections on issues rectified which are as follows:

Issues (pg 660)	**How it is addressed in the report (pg 660)**	**Objection by applicant**
The Digital Elevation Model (DEM) from Survey of India (SOI) doesn't properly represent the river course. The elevation in the river course **are higher than surrounding area.** This might have happened as vegetations in the river channel not properly accounted for while generating the DEM.	The river cross-sections at 200 m interval was provided to NIH by the Irrigation and Water Resources Department, Govt. of UP. These surveyed river cross-section data is used in the modelling study and outside the river cross-section area the 0.5 m DEM data is used	That it is pertinent to note that **on page 632, point 2** of the report clearly mentions that the said cross-sections already existed prior to the identification of the problem. Therefore, it remains unclear how the same pre-existing cross-sectional data, as **referred to on page 660**, could have been utilized to resolve the issue arising from the inaccurate representation of the river course in the DEM. The DEM does not accurately represent the river course, and

		reliance on cross-sections at 200 m intervals is insufficient to ensure scientific accuracy. Therefore, a re-survey using high-resolution DEM, detailed bathymetry, and closely spaced cross-sections is essential for a precise and legally sustainable floodplain delineation of River Budhi Ganga.
The surveyed river cross-section's locations at few sections is not on the river course alignment of DEM	The Irrigation and Water Resources Department, Govt. of UP. provided the KML file of alignment of river along with cross-sections. These alignments used as river centreline in this report	The mere use of departmental KML data, without cross-checking renders the delineation scientifically questionable and legally unsustainable. **As this KML file of alignment of river not provided to Applicant.**

7. That, the statement regarding the operation of canal is factually incorrect **(Page 677)**

On page no. 677, NIH Roorkee mentioned that:

> ***"As a conservative approach, the Runoff Coefficient of 0.9 is used as during rainy season and the canal is in operation..."***

This statement is not accepted by the applicant. The Madhya Ganga Canal system remains **non-operational during the rainy/monsoon season** or in heavy floods, as confirmed by field verification and photographic evidence by applicant. The assumption that the canal is operational during monsoon has resulted in erroneous discharge estimation and hydrological misrepresentation in the floodplain modelling. The geotagged photos are annexed herewith and marked as **ANNEXURE 2**

8. **That in the Hastinapur region**, there exists a natural stream of river which originates locally from Kaurvan region (as also visible in toposheet page no 682) and subsequently confluences with the main channel of River Budhi Ganga at Dudhli Khadar/Shimla; however, the said stream has been completely omitted from consideration in the Flood Plain Delineation Report (pg 671, 672,673,678,682 and 685), thereby rendering the report incomplete and scientifically inaccurate. This constitutes a serious **omission of factual and environmental assessment.** The Google Earth image is annexed herewith and marked as **ANNEXURE 3.**

9. That on **page no 676 point no 5.1** under the head of **Flood Frequency Analysis**

Statement in Report	Objection
Historical discharge series of for flood analysis is not available. Hence the discharge corresponding	That to **represent the catchment and sub-catchment areas very small,** the gauge sites have been selected **several kilometres** away

to100 year return period is estimated. from the rainfall data. The estimated value of catchment characteristics are given in table 5.1. It is noted that the catchment and sub catchment area are very small. The nearest three rain gauge station namely, Bijnor, Mawana and Hasanpur are selected based on the sub catchment area.	from the actual river stream. However, the report does not contain any map or detailed information delineating the catchment and sub-catchment areas of River Budhi Ganga. It is pertinent to mention that the river flows through Districts Muzaffarnagar, Meerut, and Hapur, **yet the rain gauge stations considered in the report are not situated within the actual catchment or sub-catchment area of River Budhi Ganga, thereby rendering the hydrological analysis and results unreliable.**

10. That in **Assumption and Limitations, on page 686** of the report,

According to report page no 686	**Objection by Applicant**
• *Limitation of river bathymetry below the water spread area in the SOI DEM and* ***accounted using available cross section only***	The Flood Plain Delineation Report suffers from significant methodological limitations, as the river bathymetry below the water spread area in the SOI DEM has not been properly represented and has **been accounted for merely through limited cross-sectional data.**
• *Evaporation, infiltration/groundwater interaction and diversion losses neglected.*	**The omission of critical hydrological parameters** such as **groundwater interaction**

	undermines the accuracy of the hydrodynamic modelling. **Floodplain delineation is generally incomplete without considering surface-groundwater interactions. Groundwater and surface water interaction plays a significant role in floodplain hydrology because floodplains act as the interface zones where exchanges occur between streams and groundwater systems. Refer ANNEXURE 4**

Then the flood plain delineation **cannot be considered scientifically accurate or complete.** Furthermore, Hence, the delineation prepared on such incomplete data and assumptions cannot be treated as scientifically sound or legally sustainable.

11. That **the energy equation** used for calculating the water surface profile, as mentioned on **page 674** of the report, differs from the formulation provided in the *HEC-RAS River Analysis System, Hydraulic Reference Manual*, Version 6.5, March 2024. If any modification in the formula has been made, it is necessary to specify the reasons for such alteration and clarify why the variables or alphabets have been rearranged. A copy of the relevant pages of the HEC-RAS Hydraulic Reference Manual is attached herewith and marked as **ANNEXURE 5**

12. **That, until proper and verified floodplain demarcation is completed, all activities must be stopped on River Budhi Ganga and its floodplain.** It is respectfully submitted that **no construction work, land sale, or allotment activities** should be permitted within the proposed or disputed floodplain stretch of Budhi Ganga in **District**

Muzaffarnagar, District Meerut and District Hapur till a scientifically verified demarcation is approved by the Hon'ble Tribunal after public disclosure of KML, DEM, and ground-truth data. In certain areas, including Deval in District Muzaffarnagar and Hastinapur in District Meerut and several others, construction activities are still being carried out within the floodplain of River Budhi Ganga, in contravention of the environmental safeguards and regulatory provisions governing floodplain zones.

13. **That, the model parameters and calibration details are missing (Pages 674–678).** No details are provided about **boundary conditions, mesh size, sensitivity analysis,** or **model validation** of the HEC-RAS 6.5 simulation. Manning's coefficients are arbitrarily assigned without field calibration. Such omissions invalidate the technical credibility of the modelling process.

14. **That on page 687 it is mentioned in the report that :**

Statement	Objection to the statements
However, at present there is no surface flow from the Ganga River to Budhi Ganga River in normal Condition.	Under normal conditions, the Budhi Ganga River maintains surface water flow throughout the year, except during the very dry months of May and June.
It is recommended that while conducting the Flood Plain Zoning of the River Ganga for 100-year return period flood, these tributaries may be	If it is recommended that tributaries be jointly modelled with the Ganga for 100-year flood studies then in this condition this flood plain is accepted or not ?

modelled/studied together for combined effects.	Clarification is required on how such delineation has been approved in contradiction to the stated recommendation.

Prayer

In light of the above deficiencies, contradictions, and data concealment, the Applicant most respectfully prays that the Hon'ble Tribunal may kindly:

1. Direct the **Irrigation and Water Resources Department** and **NIH, Roorkee** to submit complete datasets including DEM, KML, KMZ, and cross-section files for verification.
2. Direct **immediate suspension of all construction, sale, or allotment activities** within the suspected floodplain zone till final demarcation is approved.
3. Direct **Irrigation and Water Resources Department** and NIH to carry out a **revised and ground-truth floodplain demarcation** integrating hydrology, ecology, ground water and surface water interaction parameters as per Hon'ble NGT and Ganga Rejuvenation guidelines.
4. Pass any such and further orders as this Hon'ble Tribunal may deem fit and proper in the facts and circumstances of the case.

For all the reasons stated above the Hon'ble Tribunal may kindly be pleased to take cognizance of all these facts and to pass appropriate orders to meets the ends of Justice and equity.

AND FOR THIS ACT OF KINDNESS THE APPLICANTS, AS IN DUTY BOUND, SHALL EVER PRAY.

Verification

Verified on this 9th day of October 2025 that the contents of the present Application are true and correct to my knowledge and belief and nothing material is concealed therefrom.

Priyank Bharati

Applicant in Person

Date : 09th Oct 2025

Place : Meerut

ATTESTED 9/10/25 NOTARY

NOTARY PUBLIC AKHILESH KUMAR Advocate Regd. No. 17 Distt. Meerut GOVT. OF INDIA

BEFORE THE HON'BLE NATIONAL GREEN TRIBUNAL
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Versus

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-----RESPONDENTS

AFFIDAVIT

I, Priyank Bharati, S/o, Shri. Brahampal Singh aged about 36 years, R/o Jagriti Vihar, District Meerut, Uttar Pradesh do hereby solemnly affirm and declare as under:

1. That I am the Applicant/Applicant In Person in above mentioned application and I am fully conversant with the facts and circumstances of the case and therefore competent to swear this affidavit.
2. That the statements made in above paragraphs of this affidavit is true to my knowledge and belief.
3. That the contents of the Application are true and correct and nothing material has been concealed therefrom.

Bharati

Applicant In Person

VERIFICATION

Verified on this 09th day of October 2025 that the contents of the present Application are true and correct to my knowledge and belief and nothing material is concealed therefrom,

Bharati

Applicant In Person/Deponent

ATTESTED
9/10/25
NOTARY

Gmail

Priyank Bharati <naturalsciencestrustmrt@gmail.com>

Request for Copy of Flood Plain Delineation Report of River Budhi Ganga in Compliance with Hon'ble Tribunal's Order Dated 14.07.2025 in the matter of OA 511 of 2023.

3 messages

Priyank Bharati <naturalsciencestrustmrt@gmail.com> Mon, Jul 14, 2025 at 1:49 PM
To: bhanwar jadon <bhanwar09jadon@gmail.com>

To,
14.07.2025

Mr. Bhanwar Pal Singh Jadon,

Standing Counsel for the State of UP

Subject: Request for Copy of Flood Plain Delineation Report of River Budhi Ganga in Compliance with Hon'ble Tribunal's Order Dated 14.07.2025 in the matter of OA 511 of 2023.

Respected Sir,

I respectfully submit that during the course of hearing dated **14th July 2025**, the **Hon'ble National Green Tribunal** was pleased to direct that the **flood plain delineation report of River Budhi Ganga** be made available to Applicant.

In compliance with the said order, I hereby request that the **entire copy of the floodplain delineation report of River Budhi Ganga**, along with all accompanying maps, annexures and explanatory notes, kindly be provided to me at the earliest.

I shall be grateful for your prompt cooperation in this regard.

With regards,
Priyank Bharati

Applicant

Priyank Bharati <naturalsciencestrustmrt@gmail.com> Wed, Jul 16, 2025 at 11:07 AM
To: bhanwar jadon <bhanwar09jadon@gmail.com>, "Consultant Judicial-NGT(P.B.)" <judicial-ngt@gov.in>

Respected Sir,

I acknowledge receipt of your email dated 14th July 2025. **However, the KML file of the flood plain appears to be missing from the attachments.**

I kindly request you to provide the KML file as referred to in Point No. 10 and Annexure A1 of your communication.

Thank you for your attention to this matter.

Warm regards,
Priyank

[Quoted text hidden]

Priyank Bharati <naturalsciencestrustmrt@gmail.com> Fri, Sep 5, 2025 at 9:04 AM
To: bhanwar jadon <bhanwar09jadon@gmail.com>, cegangaidupme-up@nic.in

Respected Sir,
Kindly provide the KML file at the earliest so that I may submit my objections in OA 511/2023 within the stipulated time.

Warm Regards,

Priyank Bharati
(Applicant In Person)
Mobile : 09411823914

cc:

1. Shri Gyan Prakash Srivastava Ji , Chief Engineer-II (Ganga), Meerut

[Quoted text hidden]


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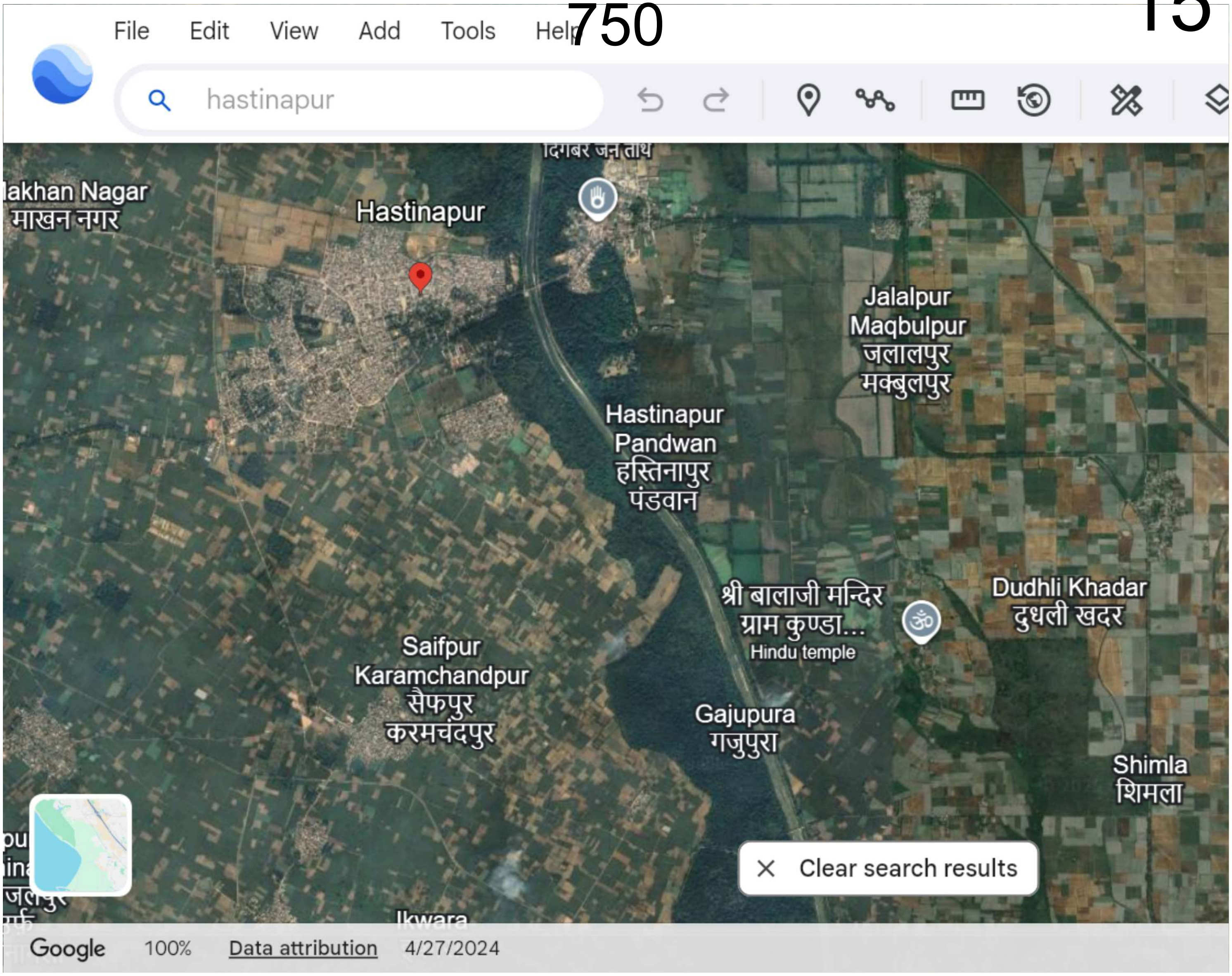
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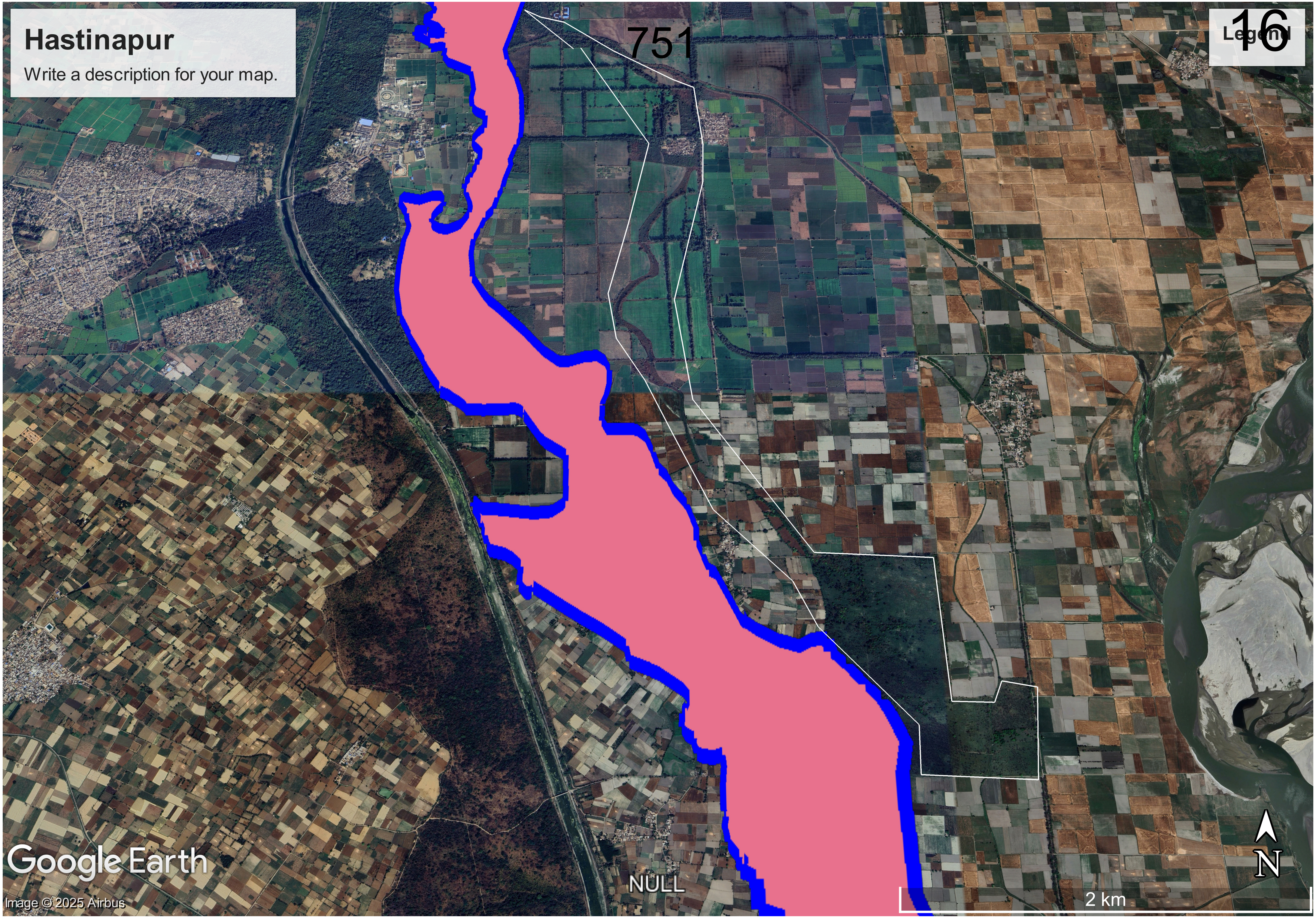
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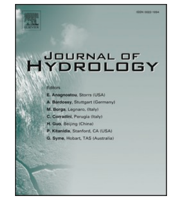

Research papers

Groundwater-Surface water interactions research: Past trends and future directions

Dylan J. Irvine [a,b,*], Kamini Singha [c], Barret L. Kurylyk [d], Martin A. Briggs [e], Yakub Sebastian [a], Douglas R. Tait [f], Ashley M. Helton [g]

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[b] National Centre for Groundwater Research and Training, Bedford Park, South Australia, Australia
[c] Hydrologic Science and Engineering Program, Colorado School of Mines, Golden, CO, USA
[d] Department of Civil and Resource Engineering and Centre for Water Resources Studies, Dalhousie University, Halifax, Canada
[e] U.S. Geological Survey, Observing Systems Division, Hydrologic Remote Sensing Branch, Storrs, CT, USA
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ABSTRACT

Interactions between groundwater and surface water sustain groundwater-dependent ecosystems and regulate river temperature and biogeochemical cycles, amongst many other processes. These interactions occur in freshwater environments including rivers, springs, lakes, and wetlands, and in coastal environments via tidal pumping, submarine groundwater discharge, and seawater intrusion. Here, we explore groundwater-surface water interactions research using bibliometric analyses of titles, abstracts, and keywords from 20,275 journal papers published between 1970 and 2023 extracted from Scopus. Analyses show that research into groundwater-surface water interactions is highly multi-disciplinary, with growing contributions from the social and biological sciences. The number of groundwater-surface water interactions papers is rapidly increasing with over 1200 papers published per year since 2020. Drawing on our data-driven approach and expert knowledge, we synthesise current research trends and identify critical future research directions. Despite the thousands of papers on groundwater-surface water interactions, important processes are still difficult to quantify or predict at meaningful spatial scales to inform water-resources management. We see benefits in future groundwater-surface water interactions research focusing on: (1) using new technologies including internet-of-things-based sensors, uncrewed vehicles, and remote-sensing approaches for data collection to inform groundwater-surface water interactions at large scales, (2) seeking approaches to upscale site-specific findings to better inform management, and (3) continuing the movement towards multi-disciplinary investigations to better inform the understanding of groundwater-surface water interactions and processes that will enable better management outcomes.

1. Introduction

Groundwater and surface water are widely recognised as interconnected hydrologic systems (e.g., Boano et al., 2014; Brunke and Gonser, 1997; Winter et al., 1998). Modern research into groundwater-surface water (GW-SW) interactions dates to the 1930 s, with multi-disciplinary GW-SW interactions research widely published across diverse fields of study including hydrogeology, hydrology, limnology, amongst many others. This multi-disciplinary focus is necessary given the broad range of processes that influence and are influenced by GW-SW interactions. For example, GW-SW exchange is a hydrological process that plays important biogeochemical and ecological roles (Ward, 2016), including regulating surface water temperature regimes (Benz et al., 2024; Hare et al., 2021), controlling processes including denitrification and the redistribution of oxygen in the hyporheic zone (Boano et al., 2014; DelVecchia et al., 2022), and sustaining riparian zone vegetation (Harvey and Gooseff, 2015). Understanding GW-SW interactions is also important in studies of baseflow (Arnold and Allen, 1999; Ladson et al., 2013; McCallum et al., 2010), bank storage (Cartwright and Irvine, 2020; Doble et al., 2012), flooding (e.g., Blöschl

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et al., 2007; Miguez-Macho and Fan, 2012), and stream depletion (e.g., Huang et al., 2018; Hunt, 2014). GW-SW exchange is driven by factors including hydraulic gradients, geologic heterogeneity (e.g., Tonina and Buffington, 2009; Wohl, 2021), and channel morphology (Cardenas and Zlotnik, 2003a; Stonedahl et al., 2010). The wide-ranging drivers and effects of GW-SW interactions intersect with many broader fields, from geology, hydrology, and fluvial geomorphology to biogeochemistry and ecohydrology.

Effective water-resources management is one of humanity's greatest priorities (e.g., Jakeman et al., 2016) given the expanding demand for water by the increasing global population and a rapidly changing climate punctuated by extreme events. Despite its importance, conjunctive management of groundwater and surface water resources is challenging. Challenges include the complexity of GW-SW systems, measuring and summarising those system dynamics at management-relevant scales and the often-fragmented decision-making process caused by the involvement of multiple agencies (Howe, 2002). Natural and human-driven changes to GW-SW systems cause a myriad of important effects, resulting in aquifers and groundwater-connected systems that function as 'socioecological systems' (Huggins et al., 2023). Therefore, a detailed understanding of the natural processes that GW-SW interactions support, and the effects of future climate change and further extraction of water resources could help inform the management of groundwater and surface water resources.

With many thousands of papers on the topic, GW-SW interactions are now a well-established research field. Here we take the opportunity to provide an overview of research trends and consider potential future research trajectories. We use the Scopus database (Elsevier, 2024) to explore GW-SW interactions research and assess publishing trends and trends in the focus of GW-SW interactions research. Open questions include how the field of GW-SW interactions has evolved since research began in earnest in the 1970 s, where the field is headed, and what are the future research needs and opportunities. To address these questions, we present a bibliometric analysis of GW-SW interactions studies published between 1970 and 2023. After providing an overview of GW-SW interactions processes (Section 2), we detail our literature review methodology (Section 3), we then focus on publishing trends through time (Sections 4.1 to 4.3), the journals and countries publishing in the field (Sections 4.4 and 4.5), and the relationships between related research areas (Section 4.6). We then investigate the current state of the field, including an attempt to identify recent work that is projected to have a major future impact (Section 5.1), and a summary of recent research trends (Section 5.2). Finally, we discuss future GW-SW interactions-research needs and opportunities (Section 5.3).

2. An overview of GW-SW interactions

2.1. GW-SW interactions, processes, and zones

Subsurface waters exchange with rivers, lakes, streams, springs, wetlands, and the ocean (Fig. 1), where dynamic hydraulic head gradients between surface waters and the adjacent groundwater control the directionality of exchange (Fig. 1b). A 'gaining' system occurs where the surface water body increases in volume through seepage, fracture flow, and macropore discharge. Conversely, a 'losing' system occurs where surface water is routed to either the saturated or unsaturated zone in the subsurface. The relationship between groundwater and surface water is dynamic in both time and space; for example, (1) rivers can gain and lose water along their length, possibly with nested gaining/losing reaches (Payn et al., 2009), (2) heavy rainfall can temporarily cause a gaining section of river to transition to losing (e.g., Fig. 1b, Doble et al., 2012), and (3) groundwater extraction can cause surface water bodies (or at least part of a river system) to switch from gaining to losing (e.g., Hunt, 2014; Zipper et al., 2022), with various processes leading to diurnal variations in GW-SW exchange (Wu et al., 2021). The difference in hydraulic head between surface water and groundwater and flow directions is consistent across all GW-SW interactions settings, including in the coastal zone (e.g., Fig. 1a, 1e) where fluid density variations influence hydraulic heads and tides induce 'pumping' exchange (e.g., Ma and Zhang, 2020; Sekar et al., 2022), and in 'disconnected' systems

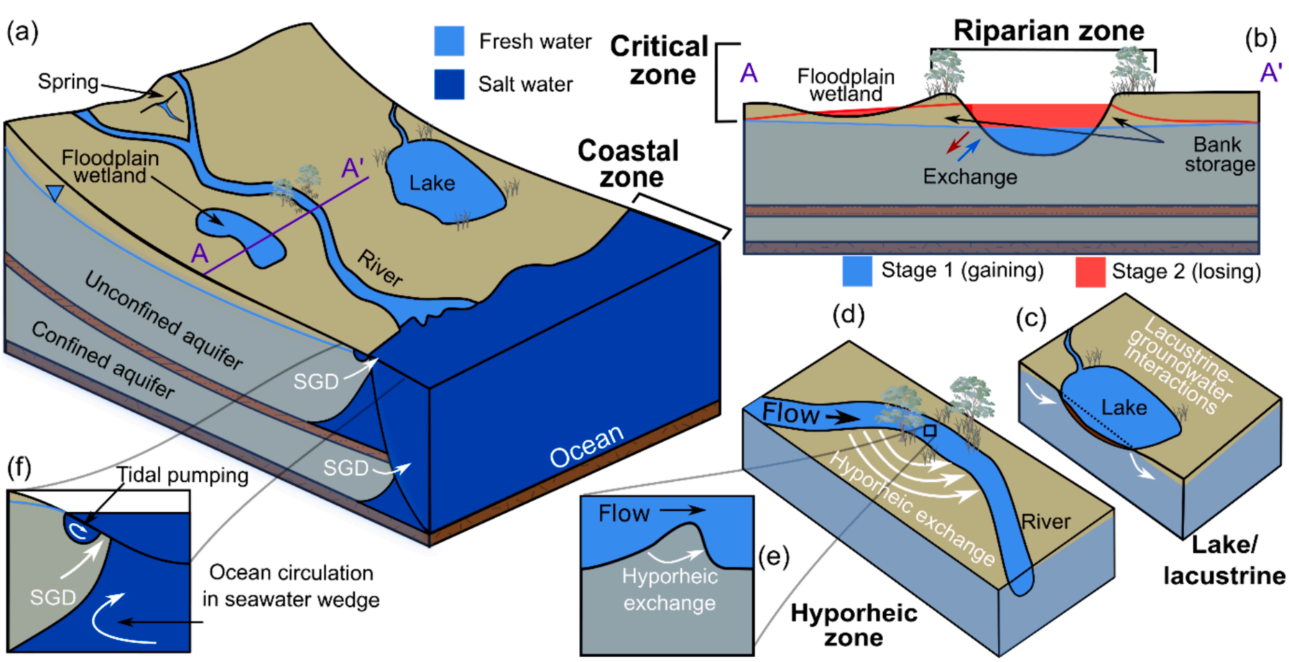

Fig. 1. Diagrams of groundwater-surface water (GW-SW) interactions throughout (a) a hydrological system including groundwater, a river and floodplain, lake, spring, and the ocean. SGD denotes submarine groundwater discharge. (b) Cross section showing the riparian zone, a floodplain wetland, the processes of bank storage, the direction of GW-SW exchanges at two river stages (blue denotes gaining conditions, red denotes losing conditions), and connections to the critical zone, i.e., from treetops to the water table (Sawyer et al., 2016b; Singha and Navarre-Sitchler, 2022). (c) Lacustrine-groundwater interactions, flow through conditions shown. (d) Hyporheic exchange (white arrows) caused by river geometry, (e) bedforms, and (f) Ocean-aquifer exchanges, including seawater intrusion, SGD, ocean water circulation, and tidal pumping.

where an unsaturated zone forms beneath surface water bodies (e.g., Brunner et al., 2009; Xie et al., 2014).

Bed materials have a strong control on GW-SW interactions, with the call for streambed science to be recognised as a scientific discipline (Constantz, 2016). GW-SW interactions are influenced by heterogeneities in aquifers and bed materials, often focusing GW-SW exchange to preferential zones of particularly strong hydrologic connectivity (e.g., Briggs and Hare, 2018; Covino, 2017). Measurements or estimates of streambed hydraulic properties can be obtained from a wide range of techniques, including hydraulic methods (e.g., Cardenas and Zlotnik, 2003a; Chen, 2000), the paired use of temperature time series and hydraulic gradients (Hatch et al., 2010), and equivalent porous media/modelling methods (Cardenas and Zlotnik, 2003a). The application of methods to estimate bed hydraulic properties is challenging in streams, creeks, and rivers, which are dynamic due to erosion and deposition events, relative to lentic settings. Brunner et al. (2017) and references therein discuss the challenges associated with the application of hydraulic methods due to the presence of thin biofilms at the water–sediment interface, and suggest that freeze-coring approaches (e.g., Ulrich et al., 2015) can help facilitate the quantification of streambed properties. Investigations into the role of streambed properties on stream-aquifer interactions include studies of chemistry and microbial composition (e.g., Knapp et al., 2017; Nelson et al., 2019) and their effect on river-aquifer disconnection (e.g., Schilling et al., 2017). Overviews of the role of the bed materials in regulating GW-SW interactions are discussed at length in reviews by Brunner et al. (2017) and Tripathi et al. (2021).

Groundwater discharge plays a vital role in sustaining surface water bodies (Hayashi and Rosenberry, 2002). For example, groundwater discharge generates river baseflow, maintaining flows through seasonal low flow and drought periods. Similarly, groundwater discharge sustains spring-fed wetlands and groundwater flow-through lakes (i.e., termed lacustrine-groundwater discharge, e.g. Meinikmann et al., (2013)). In both instances, a reduction in groundwater head, through either reduction in rainfall or groundwater extraction, will reduce the rates of groundwater discharge. In the case of springs, should the reduced groundwater head fall below the spring geomorphic threshold (the land surface, or lip of a spring vent, e.g., Currell et al., 2017), spring flow will cease, which could have major ecological or cultural impacts (Currell et al., 2020; Davis et al., 2013). However, rainfall or anthropogenic modifications can influence GW-SW interactions, switching gaining conditions to losing conditions via temporary increases in river stage (e.g., Ziliotto et al., 2021). Major rainfall events that generate streamflow can also lead to large groundwater-recharge events. Recharge routing and timing depend strongly on hydrogeologic setting, including whether groundwater flow is through primary pore spaces, or secondary pore spaces in the case of karst or fractured rock aquifers. Additionally, hydropeaking from hydropower operations can influence bank-storage processes, temporarily driving surface water into the adjacent aquifer (Fig. 1b). The return to pre-event conditions is influenced by the flood wave height, hydraulic conductivity, riverbank slope, and regional hydraulic gradients (Cartwright and Irvine, 2020; Doble et al., 2012). Despite the importance of source groundwater attributes for evaluating the baseflow resiliency of a given surface water system, baseflow generation characteristics are difficult to predict with confidence, necessitating novel model calibration and validation techniques (Barclay et al., 2022, 2020).

GW-SW interactions play an important role in sustaining aquatic and terrestrial groundwater-dependent ecosystems. For example, in arid and semi-arid zones, groundwater-fed springs can provide habitat for endemic species (Currell et al., 2020; Davis et al., 2013), provide access to water for migratory birds (Kløve et al., 2011), and sustain tree stands (Doody et al., 2015). Comprehensive reviews of spring types and their functions include those by Alfaro and Wallace (1994), Springer and Stevens (2009), and Keegan-Treloar et al. (2022). Groundwater discharge can also temporally modulate stream and river temperatures (Briggs et al., 2018; Burkholder et al., 2008), thereby increasing ecosystem niches and resilience during extreme high or low temperatures (Kurylyk et al., 2015). GW-SW exchange can also provide an important source of nutrients for aquatic ecosystems, particularly in nutrient-poor oligotrophic systems where groundwater provides the nutrients that drive patterns of primary productivity, biofilm growth that supports aquatic food webs, and even biodiversity (Naranjo et al., 2019; Valett et al., 1994).

The hyporheic zone (Fig. 1c, d) is defined as the subsurface region underlying/adjacent to lotic waters where surface water enters the sediments, mixes with groundwater, and a portion of the original surface water discharges back to the channel, often with altered chemistry, temperature, and gas content (e.g., Boano et al., 2014). The hyporheic zone has received increased research attention from disciplines including freshwater ecology, aquatic biogeochemistry, hydrogeology, geomorphology, terrestrial ecology and hydrology (Boulton et al., 2010; Harvey and Gooseff, 2015). Although no strict hydrologic definition exists for hyporheic exchange, the spatiotemporal window of relevant hyporheic flow paths and fraction of returned surface water is best judged relative to hyporheic-influenced processes of interest (Harvey et al., 2013). The hyporheic zone spans several spatial extents (Poole et al., 2008), ranging from permeable alluvial floodplains (Helton et al., 2014) to meander bends (Boano et al., 2006; Malenda et al., 2019), bedforms (Cardenas et al., 2008; Fox et al., 2014; Gomez-Velez et al., 2015) and shallow, coarse sediments beneath rivers and streams (Boano et al., 2014). The spatial extent of hyporheic zones often varies over time because of connections that influence the co-evolution of hydrodynamic, geomorphological, and hydrological processes. The hyporheic zone has been extensively reviewed, including broad reviews of hyporheic zone processes (e.g., Ward, 2016) and reviews that focus on multi-disciplinary work (e.g., Krause et al. 2011), the ecological role of the hyporheic zone (e.g., Boulton et al., 2010; Harvey and Gooseff, 2015; Stubbington, 2012), biogeochemical processes (Boano et al., 2014), and the influence of climate change on processes in the hyporheic zone (Zhou et al., 2014).

Lastly, the exchange between groundwater and the ocean is an important area of GW-SW interactions, and a major component of the global water cycle (e.g., Moore, 2010; Post et al., 2013). The interactions between fresh groundwater and saline ocean water play numerous important roles in the coastal zone. For example, submarine groundwater discharge (Fig. 1a, 1e) provides local sources of freshened water at the seafloor (Burnett et al., 2003; Taniguchi et al., 2019) and influences thermal and biogeochemical conditions important to the health of coastal wetlands, marshes (Wilson and Morris, 2012), lagoons, and estuaries (Befus et al., 2013; KarisAllen et al., 2022). Submarine groundwater discharge can be circulated (brackish) or fresh and is driven by processes across timescales ranging from seconds to millennia. These processes include waves, tides, seasonal oscillations in sea-level or water table elevation, and long-term sea-level changes (Taniguchi et al., 2019). One major difference between GW-SW interactions in freshwater and marine settings is the massive extent of the discharge area to the ocean, complicating efforts to measure submarine groundwater discharge directly and increasing reliance on tracers such as radium and radon (Garcia-Orellana et al., 2021). The role of submarine groundwater discharge has been extensively reviewed, including reviews focusing on biogeochemical processes (e.g., Santos et al., 2021) and methods to measure submarine groundwater discharge rates (e.g., Duque et al., 2020).

2.2. *Anthropogenic factors influencing coupled GW-SW systems*

The effects of both climate change (Ali et al., 2012; Uhl et al., 2022) and groundwater extraction (Vainu and Terasmaa, 2016; Yin et al., 2021) on GW-SW interactions have been documented and are expected to continue. For example, groundwater extraction and climate change have led to declines in the abundance of and biodiversity within groundwater-dependent ecosystems such as springs (Gorelick and Zheng, 2015). Groundwater extraction can lead to stream depletion, with pumped 'groundwater' possibly including intercepted water that would otherwise discharge to a river and water directly from the river (Barlow and Hess, 1993; Hunt, 2014). Many analytical solutions to quantify stream depletion have been compiled for a range of conceptual models and hydrological settings as outlined in reviews by Hunt (2014), Huang et al. (2018) and Zipper et al. (2022). Additionally, the projected influence of climate change on GW-SW-related processes have been explored across a range of contexts, and continents, including studies in Australia (Zhou and Cartwright, 2021; Zhu et al., 2020), North America (Huntington and Niswonger, 2012; Levy et al., 2020), Asia (Karthe et al., 2015; Taft and Evers, 2016), Africa (Kahsay et al., 2018; Watson et al., 2019), South America (Gomez et al., 2022; Viola et al., 2015), and Europe (Chen et al., 2018; Pulido-Velazquez et al., 2015).

Groundwater and surface waters can either be a source or the receiving environment for contaminants (Tran et al., 2015). These contaminants include excess nutrients (Santos et al., 2021), contaminants such as the 'forever chemicals' per- and polyfluoroalkyl substances (PFAS) (Briggs et al., 2020; Pétré et al., 2021), trace organic contaminants (e.g., Hamdhani et al., 2020; Heeb et al., 2012), pharmaceuticals (Lapworth et al., 2015), heavy metals (Luo et al., 2022), and pesticides (Welch et al., 2019), amongst others. Concentrations of many contaminants in groundwater can be orders of magnitude higher than in surface waters; thus even small groundwater inputs can result in large fluxes (Conant, 2004). For example, submarine groundwater discharge can be a major contributor of nutrients to the ocean, and, in some cases, far exceed the nutrient loads discharged to coastal waters by rivers (Tait et al., 2023). Similarly, phosphorous transported via groundwater can lead to risk of lake eutrophication (e.g., Kazmierczak et al., 2021; Meinikmann et al., 2015). The contribution of contaminants can be diffuse, or via preferential pathways (Moore et al., 2023; Sawyer et al., 2016a). One particular concern is that contaminants can be stored in soils or groundwater systems for decades (or longer) before being discharged to surface waters, leading to long lag times between a pollution event occurring and when negative effects are seen in surface waters (Sanford and Pope, 2013; Tait et al., 2014; Tesoriero et al., 2013). The management of contaminated groundwater discharge is challenging because once contaminants enter the subsurface, the timing, potential attenuation through the sediment profile, and pathway of discharges are complex and highly heterogeneous (Cartwright and Irvine, 2020; Conant et al., 2004; Shishaye et al., 2021). Lagged delivery of nutrients from groundwater to surface waters is particularly widespread and prevalent across agricultural regions, where groundwater-delivered nutrients can significantly delay effects of nutrient management actions on water quality (Sanford and Pope, 2013; Van Meter et al., 2018).

Nutrients may be significantly transformed or attenuated within groundwater systems (Rivett et al., 2008). The GW-SW interface is particularly important for nutrient attenuation because the high reactivity of near-surface sediments surrounding streams, rivers, lakes, and wetlands reduces excess nutrient loads and pharmaceutical inputs at the distal end of groundwater flow paths (e.g., Hillebrand et al., 2015; Lewandowski et al., 2015), though preferential flow paths may bypass reactive sediments (Hester and Fox, 2020). Nitrogen dynamics within the hyporheic zone have been studied extensively (as reviewed by Zhao et al., 2021), and it is well established that hyporheic exchange can regulate nitrogen removal by stream and river ecosystems (e.g., Hall et al., 2009; Hill and Lymburner, 1998). The distribution of available carbon for microbial nitrogen removal and retention pathways as well as hydrologic residence times within the hyporheic zone control the magnitude and spatial pattern of GW-SW-driven nutrient removal (Zarnetske et al., 2011). Given the importance of hyporheic exchange in nitrogen removal, stream restoration research and practices have evolved to restore hyporheic exchange to enhance nitrogen removal (Merill and Tonjes, 2014).

2.3. Quantifying GW-SW interactions and further data interpretation

A wide range of methods are available to quantify GW-SW exchange rates and the key parameters that control processes, over point, reach and basin scales (Hammett et al., 2022; Kalbus et al., 2006; Ma et al., 2024). The breadth of techniques and approaches to quantify GW-SW exchange is due to the wide variability of settings where GW-SW interactions occur and the broad range of disciplines that study GW-SW interactions. For example, in some instances, GW-SW exchange can be measured directly at the point scale using seepage meters (Murdoch and Kelly, 2003; Rosenberry and Morin, 2004), or at the reach scale in riverine contexts using differential gauging (McCallum et al., 2014; Ruehl et al., 2006). Other approaches are based on Darcy's law (Cardenas and Zlotnik, 2003b; Chen et al., 2009a), isotope-based tracer methods (e.g., Cranswick et al., 2014; Gilfedder et al., 2015), naturally occurring or injected noble gasses (Blanc et al., 2024; Brennwald et al., 2022, 2016), reactive tracers (e.g., Höhne et al., 2022; Knapp et al., 2017), or the use of heat as a tracer (e.g., Banks et al., 2018; Koch et al., 2016; Ruehl et al., 2006; Schneidewind et al., 2016). In addition to the broad overview of techniques to quantify GW-SW exchange rates by Kalbus et al. (2006) and Ma et al., (2024), many techniques are further detailed in dedicated reviews (e.g., Cook, 2013; Irvine et al., 2017; Kalbus et al., 2006; Rau et al., 2014), and the methods-selection tool of Hammett et al. (2022). Recent advances have produced a new suite of tracing techniques to inform water origins and GW-SW exchange rates. These advances include the ability to measure noble gasses (e.g., He, Kr, Xe) in situ using portable mass spectrometers (Brennwald et al., 2016). This has allowed the use of noble gasses in injected gas tracer tests to inform a range of processes (e.g., Blanc et al., 2024; Brennwald et al., 2022; Weber et al., 2019). Microbial source tracking is another relatively recent addition to the suite of approaches that can identify the origins of contaminants and has been used to identify bacteria sources in GW-SW systems (e.g., Duvert et al., 2019; Neave et al., 2014).

Geophysical methods are one of the more recently developed tools for exploring GW-SW interactions, where electrical resistivity methods are probably the most widely used. For instance, in one of the earliest published studies, Acworth and Dasey (2003) used electrical methods to image the naturally occurring exchange of seawater with a freshwater sand aquifer in a tidal stream. Crook et al. (2008) mapped subsurface sediment deposits in two streams using electrical resistivity, which they used to estimate hyporheic exchange based on the distribution of alluvial deposits. Interactions (recharge and salinisation) between surface seawater flooding and shallow coastal aquifers have also been mapped using electrical resistivity instruments (Cantelon et al., 2022). Electrical resistivity has been used as a process-based tool for mapping GW-SW exchanges. Singha et al. (2008) demonstrated numerically that time-lapse electrical resistivity could be used to quantify hyporheic exchange processes by comparing bulk electrical resistivity and in-stream fluid conductivity measurements during conductive tracer tests. Where tracer-laden surface water exchanges with groundwater, there is an increased hyporheic zone fluid conductivity, which persists longer than that in the stream and is imageable with electrical resistivity. Since that synthetic test, many field studies have paired electrical resistivity and in-stream tracer experiments (Cardenas and Markowski, 2011; Doetsch et al., 2012; Ward et al., 2014, 2010). We note that the resolution of electrical resistivity surveys and the subsequent influence of the reliability on our understanding of hyporheic zone processes are rarely explored in detail. For example, Zhang et al. (2023a) demonstrate how well electrical inversions could be expected to resolve various changes in a GW-SW system using tracer tests coupled with electrical resistivity in a series of numerical experiments.

Remote sensing tools have also been widely used in GW-SW interactions research (Brunner et al., 2017), and the field is expanding rapidly. For example, thermal infrared sensors mounted on drones (e.g., Watts et al., 2023), helicopters (e.g., Tamborski et al., 2015), airplanes (e.g., Torgersen et al., 2001), and satellites (e.g., Jou-Claus et al., 2021) have been used to identify zones of focused groundwater discharge that, depending on the season, manifest as cold- or warm-water plumes in surface water bodies. The spatial coverage and spatial resolution of such surveys are often inversely related. While drones provide a new, inexpensive alternative for mapping small aerial footprints at high resolution, there are ongoing challenge of thermal drift that limit sensor accuracy (O'Sullivan and Kurylyk, 2022). Remote-sensing studies often focus on mapping springs and seeps to identify thermal refuges for aquatic species (e.g., Dugdale et al., 2013), or to identify potential locations of focused contaminant loading to surface waters (Johnson et al., 2008). Other remotely sensed data types indicate vegetation health and flooding extent (Doody et al., 2014), and surface water elevation (Chen et al., 2020), which can be influential to, and influenced by, GW-SW interactions.

Field data collected to inform GW-SW interactions processes are often coupled to numerical models of groundwater, surface water, or coupled GW-SW processes to allow further interpretation of system behaviour. The widely used MODFLOW codes (e.g., Langevin et al., 2017) include various packages that can represent GW-SW interactions. For example, the RIV package can be used to represent rivers in a simplistic way using a conductance term and head differences to determine if groundwater 'discharges' to a river (i.e., is removed from the model). Surface water models including MIKE SHE (DHI, 2023), HEC-RAS (Brunner, 2020), and SWAT+ (Bailey et al., 2020; Chawanda et al., 2020) include representations of groundwater and GW-SW interactions processes. Additionally, there are approaches to couple surface and groundwater models, as well as model codes that simulate both surface water and groundwater processes in a fully coupled way, including HydroGeoSphere (Aquanty, 2015), GSFLOW (Markstrom et al., 2008) and ParFlow (Maxwell et al., 2023). However, not all investigations require numerical models, and various analytical solutions exist to assist with the additional interpretation of field data. For example, analytical solutions are widely used to interpret exchange fluxes from temperature (Hatch et al., 2006; Lin et al., 2022; McCallum et al., 2012; Schneidewind et al., 2016; Shi et al., 2024) or to quantify impacts of groundwater extraction on surface water bodies (e.g., Hunt, 2014; Zipper et al., 2022). Machine-learning approaches are also becoming more widely applied to investigate GW-SW interactions (e.g., Basu et al., 2022a; Husic et al., 2022; Yang et al., 2019).

3. Literature review methods

We used the Scopus database to search for GW-SW interactions-related research. The search criteria included Article title, Abstract and Keywords to identify research outputs from 1970 to 2023. The study period was restricted to 1970 to facilitate analyses by decade, and because only a small number of articles per year (i.e., 1–6) were available in the Scopus database prior to 1970. There is substantial heterogeneity in the terms used to describe GW-SW interactions research. As such, three groups of terms were used in the search; (1) terms that relate to groundwater or aquifers, (2) terms that relate to surface water bodies, and (3) terms that relate to "interactions" or associated processes (Fig. 2). The search was intended to be broadly representative, rather than exhaustive.

Following the original search, results were restricted to academic journal papers (i.e., excluding book chapters, conference abstracts, corrections and retracted papers). Bibliometric studies often omit papers published in languages other than English (Jackson and Kuriyama, 2019). However, the outputs of the Scopus search typically had abstracts and keywords in English even for papers published in other languages, and these papers were retained for further analysis. De-duplication was run on each output file. In addition to the main data extraction from Scopus, summary files were extracted using the "Summary Filter Count" option.

Bibliometric analyses were performed using a range of analytical approaches. Raw Scopus outputs were analysed using Python (Python Software Foundation, 2024), based on either publication year, authors, affiliations, or countries of origin. In addition to these simpler analyses, a user-driven Boolean keyword-based classification approach was used. This process used Author Keywords and Index Keywords, reclassified against user-generated lists of key terms (see Supporting Information Table S1). This process was necessary given the broad range of analogous Author Keywords used (e.g., groundwater-surface water interactions, surface water-groundwater interactions).

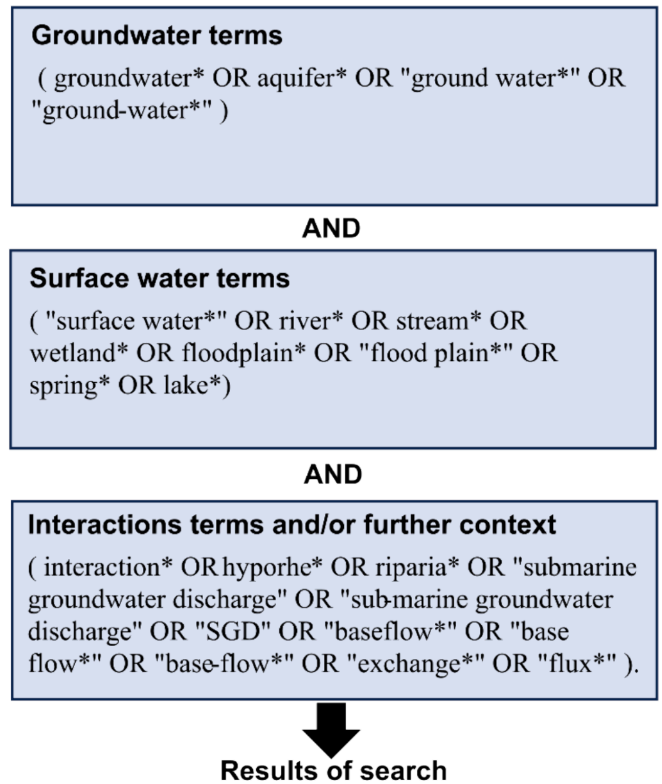

Fig. 2. Search terms used in the Scopus Article Title, Abstract, Keyword search on the 1st of January 2024. The search was limited to papers published between 1970–2023, retaining the following paper types: Article, Review, Note, Editorial, Data Paper, and Letter.

Citespace (Chen and Song, 2019) was used to conduct further bibliometric analyses based on relationships between papers by authors, keyword, or citation patterns. These investigations include Betweenness Centrality analyses to identify important papers that link subject areas and to show clusters of research, and Structural Variation Analysis to project which recently published papers are likely to be influential. Further details on the application of these techniques are provided below, and in the Supporting Information.

The Betweenness Centrality analysis was used to identify papers that indicate influence and control over the flow of information in a network of papers. This approach is predicated on the assumption that the conceptual associations between research papers can be modelled as a network of clustered papers with *co-citation* links between them. The analyses identify influential papers that serve as important links between different research areas within GW-SW interactions research. The process automatically groups the co-cited papers into clusters using an algorithm that clusters papers that share more co-citation links (Blondel et al., 2008). Betweenness Centrality approaches have been previously used to identify critical research papers in various areas of environmental studies (e.g., Shen et al., 2023; Wen et al., 2023; Zhang et al., 2023b).

Structural Variation Analysis is used to measure the intellectual values of a new research paper based on the amount and type of changes it exerts on the current research landscape at the time of its publication.

Structural Variation Analysis scores have been shown to be positively correlated with the paper's future high citation count (Chen, 2012) and have provided useful early indicators of future Nobel Prize-winning papers (Sebastian and Chen, 2021). Here, Structural Variation Analysis was used to identify "promising" recent papers before they accrue a substantial number of citations. The extent to which a paper is considered promising is measured by the new connections generated between previously unlinked research areas over timeframes of one and five years prior to the publication of the paper. Although not initially designed as filtering mechanisms, these analyses present one approach to help researchers navigate through the proliferation of GW-SW papers by highlighting important or promising papers.

The methods and results of additional CiteSpace analyses into 'author bursts', whereby authors have a 'burst' of citations over time periods of 1–5 years is presented in the Supporting Information.

4. Analyses of GW-SW interactions research

The original Scopus search returned a total of 23,077 documents. After removing non-academic journal articles, corrections, and retracted papers, restricting outputs between 1970 and 2023, and de-duplication, 20,275 journal articles remained for further analysis.

4.1. Trends in GW-SW interactions research

The number of GW-SW interactions papers published has steadily increased through time (Fig. 3), as similarly observed in other disciplines (e.g., Gxokwe et al., 2020; Jägerbrand et al., 2022; Padilla et al., 2018, see Fig S1, Table S2). In the case of GW-SW interactions research, the number of papers published approximately tripled from the 1970 s to the 1980 s, and again from the 1980 s to the 1990 s, with 164, 525, and 1566 papers, respectively (Fig. 3). From 2000 onwards, the number of GW-SW interactions papers has continued to expand rapidly, with 3980, 8829, 5211, papers published in the 2000 s, 2010 s, and 2020–2023, respectively. The maximum number of papers published in any given year (1396) was in 2021. While there is year-to-year variability in the number of publications, paper numbers post-2020 were likely impacted by COVID (Abramo et al., 2022), particularly in the case of laboratory and field-based research.

The increasing number of GW-SW interactions papers has resulted in trends in the number of authors and references per paper. For example, the average number of authors per paper increased from 1.5 in 1970, to a peak of 5.6 in 2022 (Fig. 4a). This increase is approximately linear from 1980 onwards, more than doubling throughout the study period. The average number of references per paper has also steadily increased, from less than 10 in 1970 to more than 60 from 2020 onwards (Fig. 4a). This increase is not surprising because of the increasing volume and accessibility of literature and the increasingly interdisciplinary nature of GW-SW interactions research. The rising number of references per paper follows the trends identified across other disciplines, with an increasing number of references cited per article through time (e.g., Dai et al., 2021).

The citations data (Fig. 4a) show much more complex trends than for authors and reference data. The average citations/paper prior to 1980 is erratic from year to year, because of the low number of papers published during this period (see Fig. 3) and the relatively high percentage of papers that were never cited (Fig. 4b). Between 1980 and 2000, the average citations/paper steadily increased from 22 in 1980 to approximately 60, peaking at 79 in 1998 (Fig. 4a). From approximately 2000 onwards, the number of citations/paper steadily decreased (Fig. 4a). More fundamental studies were published in the 1990 s (e.g., Brunke and Gonser, 1997; Constantz et al., 1994; Harvey and Bencala, 1993; Winter, 1999) and the early-mid 2000 s (Hatch et al., 2006; Kalbus et al., 2006; Ruehl et al., 2006; Woessner, 2000), and a strong case can be made for the recent proliferation of publications reducing the impact per paper of more recent work.

Papers cannot be cited immediately because subsequent works need to make their way through the peer-review process. Accordingly, Fig. 4b presents citations/year data normalised by the number of years since the paper was published. This approach assumes whole years and rounds up, thus a paper published in December of any given year is slightly disadvantaged in this process. The normalised citation values (Fig. 4b) peak in 2019, with a value of ~ 4 citations/paper/year published.

The number of authors per paper has steadily increased since approximately 1990 (Fig. 4a). This pattern is also observed in other hydrologically similar investigations, including investigations into nitrate leaching (Padilla et al., 2018), groundwater remediation (Zhang et al., 2017), and river health (Wen et al., 2023); refer to Supporting Information for comparisons. With increases in authors/paper across multiple research fields, it is likely that increases in the number of authors per paper have more to do with the general trend to conduct research in larger networks within and across disciplines.

4.2. Document type of GW-SW interactions research

Journal articles can be published in a range of formats, with Article and Review formats being the most common and the most cited in GW-SW interactions research (30.3 and 70.0 mean citations per paper, respectively, Table 1). In the case of GW-SW interactions research, most papers follow the Article format (19,529, ~96 %, Table 1). Of the remaining papers, only 13 are identified as Data Papers (i.e., the focus of the paper is the collation of a large dataset). These Data Papers appear to follow the recent move towards open science and the increased accessibility of resources to host online datasets (e.g., Hydroshare (CUASHI,

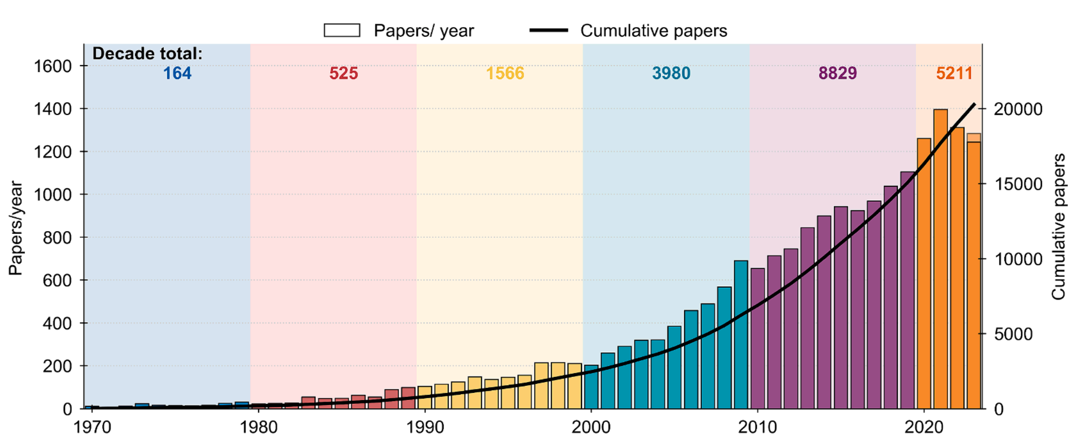

Fig. 3. GW-SW interactions papers by year (bars) and cumulative research outputs (black line) from 1970 to 2023. Colours denote decades.

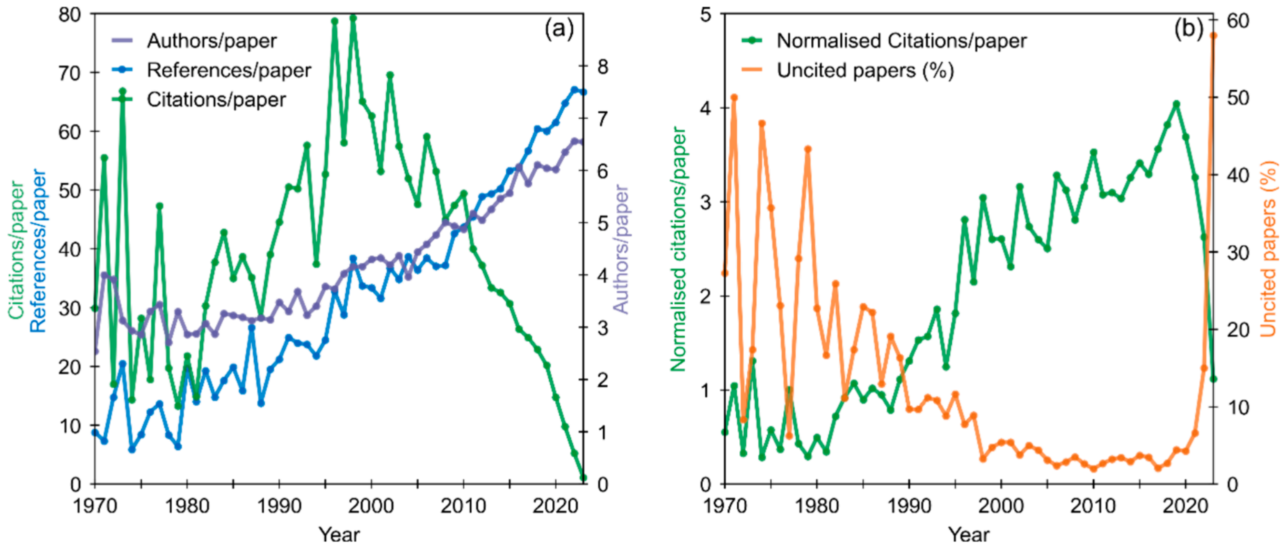

Fig. 4. Groundwater-surface water interactions research trends using the following details for any given year: Total papers (TP), total references (TR), total authors (TA), citation count (CC) and years since publication (YP). (a) Average citations/paper (CC/TP) and average references/paper (TR/TP) (primary y-axis) and average authors/paper (TA/TP) (secondary y-axis). (b) Normalised citations/paper, calculated as CC/TP/YP (primary y-axis), and uncited papers (%) (secondary y-axis).

Table 1
Groundwater-surface water interactions paper type, by decade. The mean citation column is mean citations by paper type, between 1970 and 2023.

Document Type	1970—1979	1980—1989	1990–1999	2000–2009	2010–2019	2020–2023	Total Papers	Mean citations
Article	162	521	1534	3832	8535	4945	19,529	30.3
Data Paper	0	0	0	0	1	12	13	1.1
Editorial	0	0	0	4	9	9	22	12.6
Letter	0	2	1	2	9	7	21	17.7
Note	0	0	5	13	14	13	45	18.4
Review	2	2	26	129	261	225	645	70.0
Total	**164**	**525**	**1566**	**3980**	**8829**	**5211**	**20,275**	**25.0**
Papers/day	**0.04**	**0.14**	**0.43**	**1.09**	**2.42**	**3.57**		

2024), Figshare (2024), ScienceBase (U.S. Geological Survey, 2024a)), with all Data Papers being published in or after 2019. The published Data Papers collated datasets on submarine groundwater discharge, radon and radium data (Duque et al., 2019; Wolfe et al., 2023), hydrochemistry (Ba et al., 2023; Pan et al., 2022; Rumuri, 2020), and stable isotopes (Kalvāns et al., 2020; Tetzlaff et al., 2023), typically with a local or regional focus.

Although the GW-SW interactions papers collated in this study are admittedly broad in nature, the number of Review papers and the rate of increase in publications through the decades is remarkable. For example, on average, 1.09, 2.42 and 3.57 papers were published per day in the 2000 s, 2010 s and 2020 s, respectively. The fact that there are 645

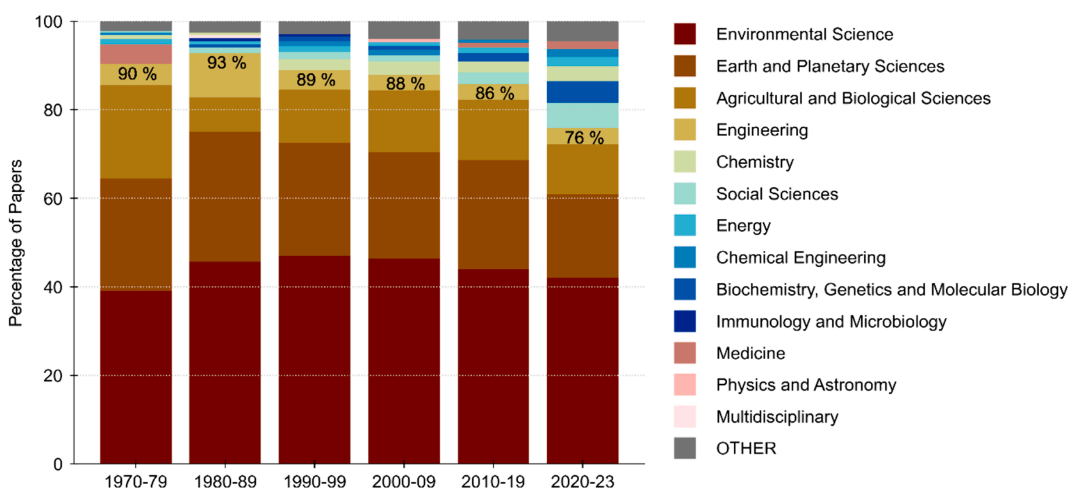

Fig. 5. Top 10 subject areas of published GW-SW interactions papers, by percentage of papers published by decade. Subject areas as classified by the Scopus database. Subject areas outside of the yearly top 10 are grouped into "OTHER". Black numbers denote the combined percentage of papers in Environmental Science, Earth and Planetary Sciences, Agricultural and Biological Sciences and Engineering (EEAE) papers for each decade.

Review papers, 225 of which have been published since 2020 (Table 1), further highlights the challenges of keeping up with the literature, even review papers (the irony of making this point in a review paper is not lost on us). The challenge of staying up to date with relevant research has also been documented in smaller, but rapidly growing disciplines (e.g., Tague and Brandt, 2023).

4.3. Scopus subject areas through time

Research in GW-SW interactions is often multi-disciplinary by necessity, given the broad range of processes that influence and are influenced by surface–subsurface hydrologic exchanges. Four fields—Environmental Science, Earth and Planetary Sciences, Agricultural and Biological Sciences, and Engineering (herein the EEAE subject areas)— contribute the largest number of GW-SW interactions papers (Fig. 5). The total contribution of the EEAE subject areas has consistently declined since the 1980 s. For example, the total contribution of the EEAE subject areas decreased from 93 % of papers in the 1980 s to 76 % of papers in the 2020 s (so far). Interestingly, Engineering is not featured in the top four subject areas in the 2020 s, following a large growth in the subject areas of Social Sciences, Biochemistry, Genetics, and Microbiology. Overall, the decadal trends in subject area (Fig. 5) suggest that GW-SW interactions research is becoming increasingly multi-disciplinary.

Many of the subject areas that make up a smaller percentage of GW-SW interactions papers are categorised into somewhat curious subject areas, including medicine. In this example, the research identified as having a medical focus generally studied the transport of various chemicals including antibiotics (e.g., Li et al., 2023) or PFAS (e.g., Tokranov et al., 2021) and legacy contamination events (e.g., Dwivedi et al., 2022). The percentage of studies that are outside of the top 10 (labelled here as “OTHER”, Fig. 5), increase from < 1 % in the 1970 s to 4.6 % in the 2020 s, further demonstrating the increasingly multi-disciplinary nature of GW-SW interactions research.

4.4. Journals publishing GW-SW interactions research

GW-SW interactions research has been published in over 2000 different journals between 1970 and 2023. The top 15 journals, by number of GW-SW interactions papers published (Fig. 6) collectively comprise 7584 (37 %) of the total GW-SW interactions papers considered in this analysis. The *Journal of Hydrology* has published the most articles, with 1543; this count did not include the relatively new *Journal of Hydrology X*. The count for *Groundwater* included both *Ground Water* and *Groundwater*, following the name change of the journal in 2013.

Many of the journals in the top 15 (Fig. 6) were founded during the timeframe of the study (1970–2023). For example, the first edition of *Science of the Total Environment* and *Hydrogeology Journal* was released in 1992. The first edition of *Environmental Earth Sciences* was published in 2009, and the first issue of *Hydrology and Earth System Science* was published in 1997. The most recently added journal from Fig. 6, *Water*, was first released in 2009. Despite its relatively recent release, *Water* ranks seventh on the number of GW-SW interactions publications, publishing a high volume of papers, with an overall lower citation rate per article (9.5 citations/paper) than other journals (e.g., *Journal of Hydrology*, *Water Resources Research* and *Hydrological Processes* receive 39.3, 52.9 and 33.3 citations/paper, respectively). The citations of these papers are at least partially affected by the age of the papers, and the time that they have had to be cited. However, it is worth noting that there is controversy surrounding whether or not *Water* is a predatory journal (MDPI, 2023; Predatory Reports, 2022). In contrast, *Environmental Science & Technology* papers attract higher citations, on average (64.9), than all other journals.

4.5. GW-SW interactions papers published by country

GW-SW interactions papers have been published by authors from at least 159 different countries between 1970 and 2023 (Fig. 7). The top five publishing countries over the study period, by total papers published, are the United States (6568, 23.4 %), China (3176, 11.3 %), Germany (1658, 5.9 %), Canada (1428, 5.1 %) and Australia (1290, 4.6 %). The top five publishing countries account for 50.3 % of the GW-SW interactions papers in the study period. The top 10 countries (also including the United Kingdom, France, India, Italy, and Spain) account for 66.6 % of GW-SW interactions papers from the study period. The number of publications produced per country is influenced by factors

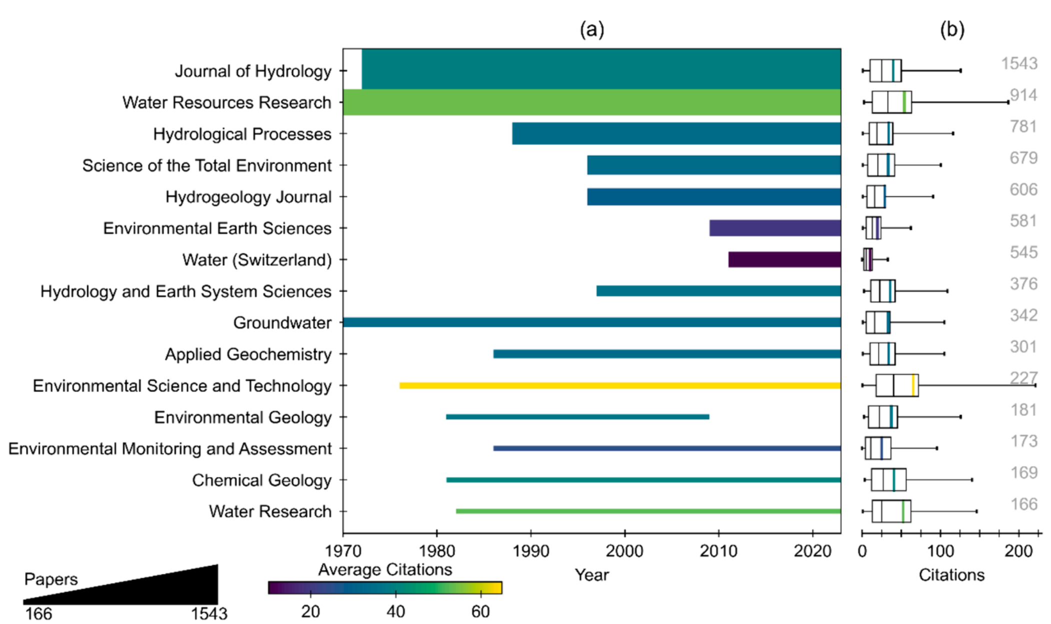

Fig. 6. Publications data for GW-SW interactions research published between 1970 and 2023. (a) Publications by journal (y-axis), year range (x-axis), average number of citations per document (colour) and total number of publications (thickness). In panel (a), the length of the lines denotes the years where papers appeared from that journal in the Scopus search. (b) Boxplots of citations with 5 and 95th percentiles as the whiskers, 25th and 75th percentiles as the edges of the boxes, black lines as the 50th percentile, coloured line as the arithmetic mean citation, and grey numbers denoting the number of papers.

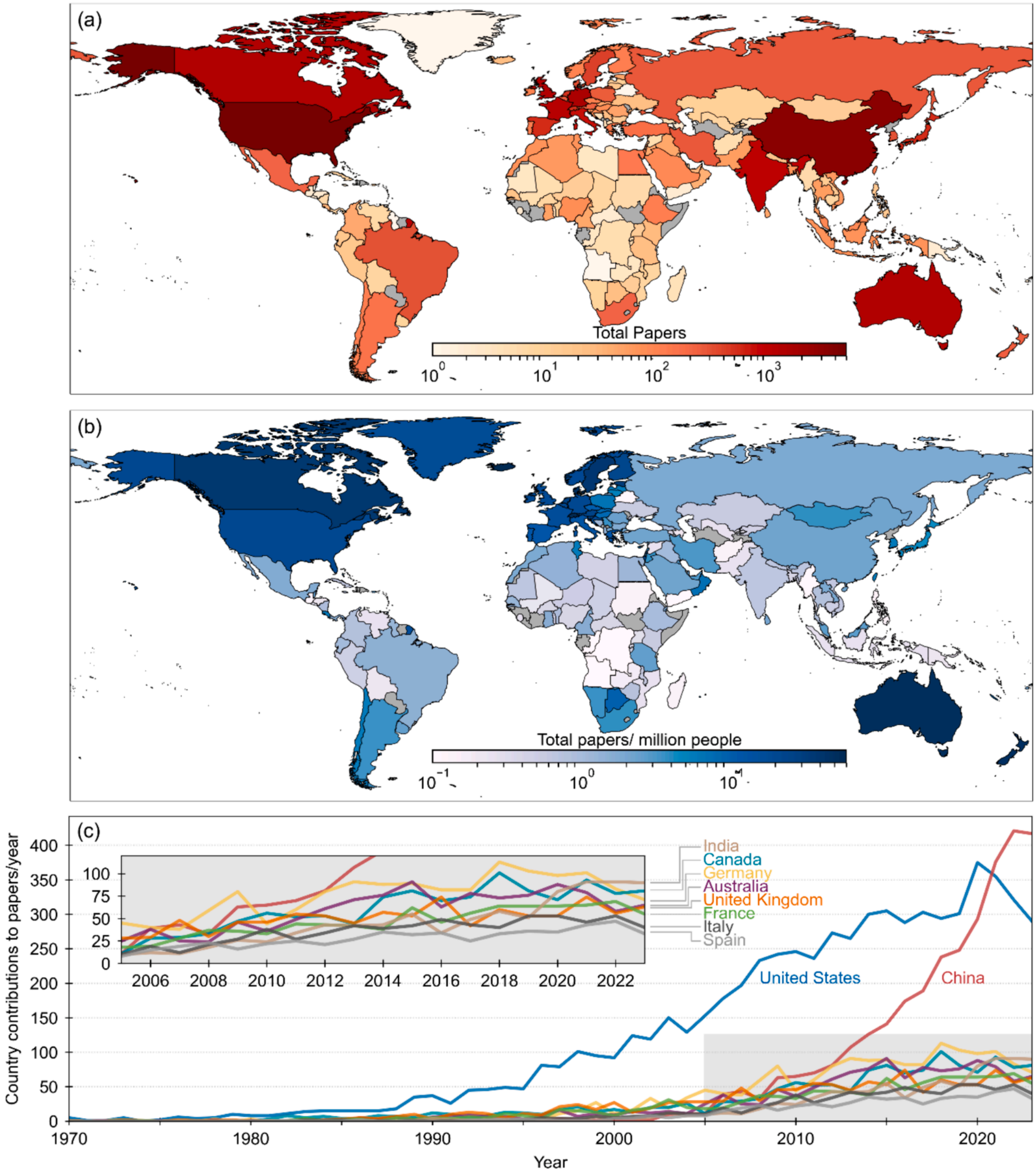

Fig. 7. Country contributions to GW-SW interactions papers published between 1970 and 2023. (a) Total number of GW-SW interactions papers for each country. (b) Total papers for each country per million people. Population data from Jan 2020 was used (United Nations, 2022). Countries with no data are shown in grey. (c) Country contributions (papers/year) over time for the top 10 publishing countries, with the inset panel showing papers from 2005 to 2023.

including population size and level of economic development, amongst others. Although we do not account for economic status, we do present paper outputs normalised by population (Fig. 7b). The top 10 countries, using the population normalised metric of papers per million inhabitants, were Monaco (162.0), Iceland (63.1), Switzerland (59.8), Denmark (51.1), Australia (50.5), New Zealand (49.3), Luxembourg (43.1), Sweden (38.6), Canada (37.8) and Estonia (33.1).

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Publishing rates of GW-SW interactions papers have varied significantly across different countries (Fig. 7c). Until 2021, the US published the most GW-SW papers in any given year, with an approximately linear increase in the papers/year between 1990 and 2020 ($R^2 = 0.97$). In 2021, China passed the US in papers/year, with an almost exponential increase in the number of papers/year between 2000 and 2023 ($R^2 = 0.94$). Incidentally, the rate of research outputs from China seems to be less affected by COVID compared to other countries, i.e., post-2019. For example, there is an observable decline in GW-SW papers/year from the US, post-2020; however, declines over this period also occurred in Germany and Australia, and research outputs in many other countries have been relatively constant (Fig. 7c). The decline in 2023 can be partially attributed to delays in some papers being listed on Scopus at the time of the search.

4.6. Identifying connections between papers using Betweenness Centrality analyses

To assess the importance of individual research papers beyond their citation counts, we applied a well-established measure in the field of network science called Betweenness Centrality (Freeman, 1977; Newman, 2005). The co-citation network of GW-SW interactions papers from 2000 to 2023 (Fig. 8) shows the output of the Scopus search as a network of research areas (clusters). Each cluster is labelled with the most salient terms automatically extracted by the Latent Semantic Indexing algorithm (Deerwester et al., 1990) from the titles of citing papers, showing distinct research subfields. For example, Cluster #0 *submarine groundwater* denotes the largest cluster, noting the prevalence of research in this area since 2000. Papers labelled by blue text (Fig. 8) are the top-four research papers with the highest Betweenness Centrality scores (see Table 2), with these papers providing strong links between research areas.

The links between individual papers and those that link the research clusters was identified using Citespace and shown in Fig. 8. For example, the large number of links between #2 "Hyporheic exchange" and #3 "Using heat" is clear, given the wide use of heat as a tracer to quantify exchanges in the hyporheic zone. However, some of the classifications differ from what would be the case if this process were done manually. For example, the Sophocleous (2002) review is broad in nature and could fit in many categories presented here. Similarly, the Boulton et al. (1998) review, focused on the hyporheic zone, and covered concepts well beyond headwater streams (the cluster that it was assigned to). The challenge in categorising these papers, amongst others, is further demonstrated in Table 2, where some papers link large numbers of research clusters. For example, the Sophocleous (2002) review links seven and Boulton et al. (1998) links five research clusters. Although this could be an unsurprising result, the approach presented here demonstrates the ability of some papers, typically reviews, to link various aspects of GW-SW interactions research together.

There are notable exclusions from Table 2, given its focus on academic papers. There are highly influential reports that do not feature in the analyses presented here, including the report *Ground water and surface water – A single resource* by Winter et al. (1998). The report has been widely influential, because it provides overviews of key concepts and several U.S. examples of GW-SW interactions studies. As the title clearly states, the Winter et al. (1998) report makes the case for groundwater and surface water to be managed as a single resource, an approach that was not common at the time the report was published.

High BC score papers (Table 2, Fig. 8) identify opportunities for techniques to be applied to inform multiple processes and/or document impacts on GW-SW interactions systems. These papers are, in most cases, review papers, and are 10 to 25 years old, providing sufficient time to be cited. Review papers are also cited more than Articles, on average (Table 1). Non-reviews in Table 2 include the Cardenas (2008) paper that demonstrates the control of geomorphology on residence times, and the Cardenas (2009) paper that demonstrates the control of

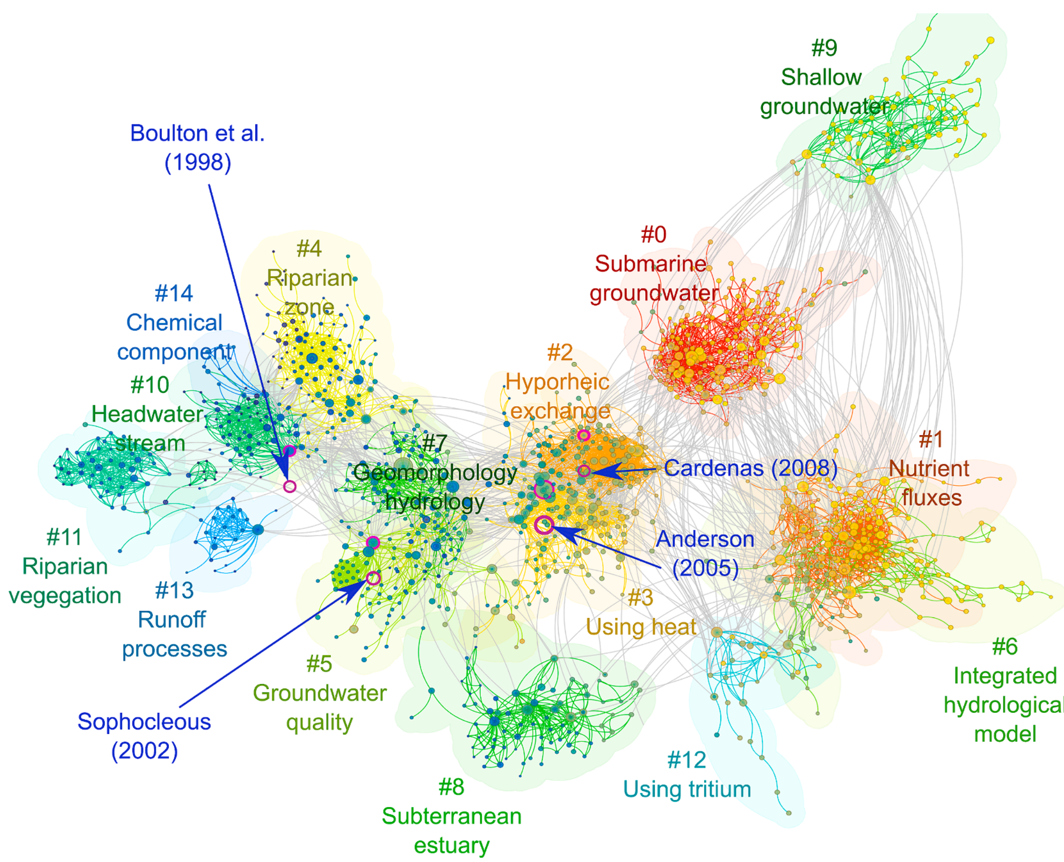

Fig. 8. Betweenness Centrality analysis of GW-SW interactions papers between 2000–2023 for clusters 0 to 14. Betweenness Centrality analyses identify clusters of (nodes) papers, and papers that are important links between clusters. Named/ numbered clusters (as identified by the Citespace software) in descending order of its sizes: **0**: *submarine groundwater*; **1**: *nutrient cycling*; **2**: *hyporheic exchange*; **3**: *using heat*; **4**: *riparian zone*; **5**: *groundwater quality index*; **6**: *integrated hydrologic model*; **7**: *geomorphology hydrology*; **8**: *subterranean estuary*; **9**: *shallow groundwater*; **10**: *headwater stream*; **11**: *riparian vegetation*; **12**: *using tritium*; **13**: *runoff processes*; and **14**: *chemical component*. The blue labelled papers partially identify the top papers by Betweenness Centrality scores and the size of their associated pink nodes indicates strength of Betweenness Centrality score. Table 2 provides further details on the top 10 papers by Betweenness Centrality score.

Table 2
Top 10 papers by Betweenness Centrality (BC) scores (see Fig. 8). These papers provide important links between and within research clusters. For cluster numbers and names, see Fig. 8. In addition to BC score, the square brackets include the number of citations in Google Scholar (GS) and Scopus (S) on June 14, 2024.

Rank: BC score [GS/S]	Paper reference	Title	Linked research clusters
1: 0.22 [165/ 213]	Cardenas (2008)	Surface water-groundwater interface geomorphology leads to scaling of residence times	0, 2, 3, 5, 7, 12
2: 0.20 [901/ 1520]	Anderson, (2005)	Heat as a ground water tracer	0, 2, 3, 5, 7, 10, 14
3: 0.12 [945/ 1546]	Boulton et al. (1998)	The functional significance of the hyporheic zone in streams and rivers	3, 7, 10, 11, 14
4: 0.11 [1417/ 2502],	Sophocleous (2002)[1]	Interactions between groundwater and surface water: the state of the science	2, 3, 4, 5, 7, 8, 10
5: 0.10 [234/ 380]	Fleckenstein et al. (2010)	Groundwater-surface water interactions: new methods and models to improve understanding of processes and dynamics	0, 1, 2, 6, 12
6: 0.08 [372/ 594]	Constantz (2008)	Heat as a tracer to determine streambed water exchanges	0, 1, 2, 3, 4, 6, 7
7: 0.08 [661/ 887]	Boano et al. (2014)	Hyporheic flow and transport processes: Mechanisms, models, and biogeochemical implications.	0, 1, 2, 6, 9
8: 0.08 [1132/ 1835]	Brunke and Gonser (1997)	The ecological significance of exchange processes between rivers and groundwater.	4, 7, 10, 11, 13
9: 0.07 [151/ 218]	Cardenas (2009)	Stream-aquifer interactions and hyporheic exchange in gaining and losing sinuous streams.	0, 1, 2, 3, 5, 6
10: 0.07 [463/ 594]	Santos et al. (2012)	The driving forces of porewater and groundwater flow in permeable coastal sediments: A review.	0, 1, 6

[1] The Sophocleous (2002) article was flagged for plagiarism (e.g., Voss, 2015).

bedforms on in-channel flow fields for gaining and losing conditions. The Fleckenstein et al. (2010) paper, although labelled as an 'Article' in Scopus, is a short review with two main components: (a) an overview of GW-SW interactions research, summarising the influence of reviews by Sophocleous (2002), Winter (1999), and Woessner (2000), and (b) a high-level summary of the content from a special issue into GW-SW interactions, of which it is the first article.

5. Recent trends and future opportunities in GW-SW interactions research

5.1. *Projecting important papers using Structural Variation analysis*

Here, we seek to identify papers that may substantially influence on the discipline in the near future using the Structural Variation Analyses (SVA) (Table 3). In SVA analyses, papers that create important yet previously absent links between other groups of existing research papers may have a higher probability of receiving more citations and being seen as transformative (Chen et al., 2009b; Sebastian and Chen, 2021). Papers that introduce new co-citation links in ways that significantly altered the prior distribution of Betweenness Centrality scores of all existing papers (see Fig. 8) are likely to be scientifically more promising than those that did not (Sebastian and Chen, 2021). SVA analyses were run using papers published during the last five years (2019–2023), and the keyword grouping (Table S1) that corresponds with the research topics of coastal processes, nutrients and nutrient cycling, the hyporheic zone, and the riparian zone.

Table 3
Projected future impactful papers from Structural Variation Analysis from selected research clusters from Fig. 8. Keyword groups are documented in Table S1.

Projected high impact papers	Description of research
Keyword group: Coastal zone	Cluster number: #0 – Submarine groundwater
Claude et al., (2019)	Use of Radium mass balance to detect SGD in karst settings.
Xiong et al., (2022)	Environmental management and seawater intrusion in China.
Martínez-Pérez et al. (2022)	Multi-disciplinary approach to characterising SGD and seawater intrusion.
Keyword group: Nutrients	Cluster number #1 – Nutrient fluxes
Wallace et al. (2020)	Reactive transport modelling in a coastal GW-SW system and nitrification processes.
Ping et al., (2023)	Numerical modelling to investigate the role of particulate organic carbon deposition on nitrate reduction in the hyporheic zone.
Ping et al. (2021)	The role of bank storage processes in the removal of nitrate from surface waters.
Keyword group: Hyporheic zone	Cluster number: #2 – Hyporheic exchange
Singh et al. (2022)	Coupled surface–subsurface model with reactive transport to demonstrate effect of peak flow events on denitrification.
Herzog et al. (2019)	Numerical modelling analyses to demonstrate nested hyporheic exchange in headwater streams.
Wilhelmsen et al. (2021)	Laboratory and numerical modelling study to demonstrate the influence of log jams and branching on hyporheic exchange.
Keyword group: Riparian zone	Cluster number: #4 – Riparian zone
Sterte et al. (2022)	Relating groundwater transit times to dissolved organic carbon and carbon budgets in surface waters.
Blaurock et al. (2022)	The role of riparian microtopography and dissolved organic carbon and dissolved organic matter in a forested catchment.
Nogueira et al, (2021)	The role of transit times and temperature in aerobic respiration and denitrification processes.
Ping et al. (2021)	The role of bank storage processes in the removal of nitrate from surface waters.

Where most of the papers identified in Table 2 were reviews, the studies identified in Table 3 are largely studies of processes and field sites. For example, numerical modelling features prominently in the studies in Table 3 (e.g., Herzog et al., 2019; Sterte et al., 2022; Nogueira et al., 2021; Ping et al., 2023; Singh et al., 2022; Wallace et al., 2020; Wilhelmsen et al., 2021). Many papers also describe field-based studies (e.g., Blaurock et al., 2022; Claude et al., 2019; Sterte et al., 2022; Martínez-Pérez et al., 2022; Nogueira et al., 2021; Ping et al., 2021; Wallace et al., 2020).

5.2. *GW-SW interactions keyword trends*

The review to this point has focused on providing a summary of the research field and publishing trends. From herein, the focus switches to be forward looking. As part of this transition, we first look at research outputs through time, with a focus on recent trends through the assessment of the published papers in key topics. Normalising by the number of GW-SW interactions papers each year facilitates the analysis of research trends and mitigates the influence of the overall annual increase in scholarly output (Fig. 9). The increased breadth of GW-SW interactions research (e.g., Fig. 5) can also make the interpretation of these results challenging, particularly for keywords that become less prevalent through time. Nonetheless, keywords that increase through time do so despite the increasingly broad research focus of GW-SW interactions research.

Most GW-SW interactions studies focus on rivers and streams

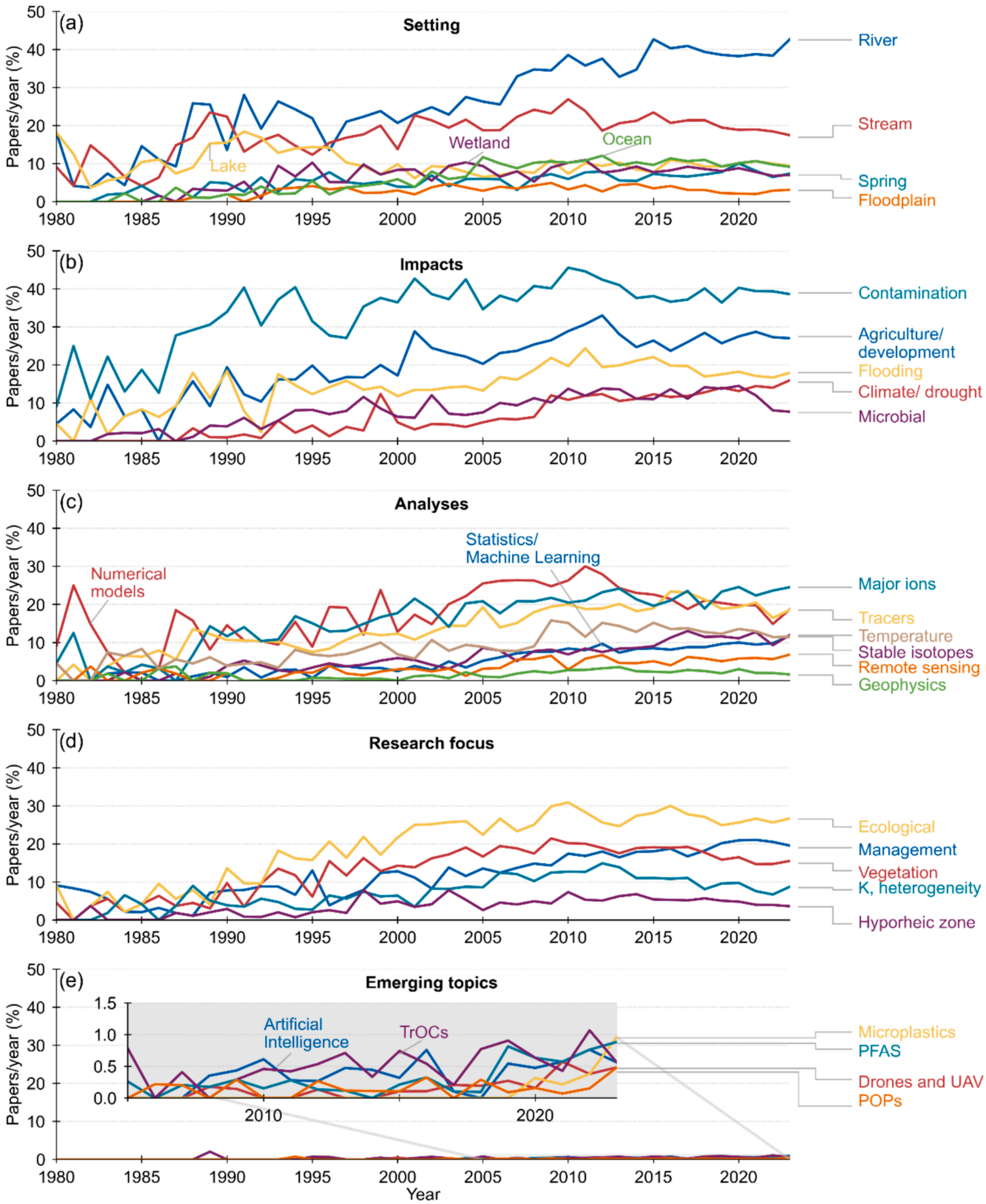

Fig. 9. GW-SW interactions research trends identified by grouping Author Keywords (see Table S1 for details on the Keyword grouping approach) from 1980 to 2023. The panels show publishing trends by (a) surface water type, (b) impacts investigated, (c) data collection and data analysis methods, (d) specific research focus (K denotes hydraulic conductivity), and (e) emerging topics (PFAS denotes Per- and polyfluoroalkyl substances, TrOCs denotes Trace Organic Compounds, and POPs denotes Persistent Organic Pollutants). The percentages for any given year do not necessarily add to 100, as papers can include multiple keywords, and/or papers may not include any of the keywords for any given panel. 1970 s papers are omitted because the outputs (as a percentage) are erratic during this period due to the low number of papers published.

(Fig. 9a), with keywords that indicate river-related research increasing since 1995. Studies of the coastal zone show a steady increase until 2005, after which they remain relatively constant. Papers investigating drought and climate have increased over the timeframe of the papers considered here (1970–2023), with a particularly large increase starting in 2016 (Fig. 9b). A noteworthy percentage of papers (~40 %) include some mention of contamination. This has been reasonably consistent since the 1990 s. From the investigation techniques (Fig. 9c), increases in the use of machine learning and remote sensing are evident. For example, the increased use of remote sensing provides opportunities to upscale site-specific findings to broader scales to further inform management. Use of machine-learning approaches has also steadily increased (Fig, 9c). The observed decline in the relative number of papers with terms relating to 'numerical modelling' since 2010 was unexpected. This is surprising given the continued increase in computational power and wide availability of numerical models capable of simulating fluid flow, solute and heat transport, including coupled surface–subsurface models as well as open access packages.

We also identify what we consider to be emerging research areas, noting that there is no formal definition for these areas (Fig. 9e). For example, contaminants, including PFAS, Trace Organic Compounds (TrOCs), and microplastics (among other chemical groups not highlighted in our analysis) are beginning to be featured in GW-SW interactions research. The dynamic conditions of GW-SW exchange may be particularly important in the fate and transport of PFAS given its sorption and speciation characteristics at multiple interfaces between groundwater, surface water, and soils (Divine et al., 2023). Open questions about how quickly PFAS are moving from aquifers to streams and the time needed to flush PFAS from aquifers remain unanswered (Briggs et al., 2020; Pétré et al., 2021). For example, fluctuations in GW-SW fluxes drive biogeochemical changes that can lead to seasonal variations in perfluoroalkyl acid concentrations and precursor loss (Tokranov et al., 2021). To date, there has been limited numerical simulation of GW-SW transport of PFAS, undoubtedly because modelling codes capable of simulating PFAS transport through variability saturated media have been only recently published (Brusseau et al., 2020; Guo et al., 2020; Silva et al., 2021).

The use of uncrewed vehicles, including aerial or aquatic vehicles (UAVs, or drones) is steadily advancing many research fields within the geosciences, including the study of GW-SW interactions (e.g., Mangel et al., 2022; Fig. 9e). Importantly, UAVs allow for precise, georeferenced surveys across landscapes or water bodies that are difficult to traverse by boat or by foot, including protected or contaminated water bodies, zones with unexploded ordinances, boggy or snowy terrain, and steep slopes. Although UAVs have been used for several years to construct digital elevation models using structure-from-motion photogrammetry for the study of GW-SW exchange (e.g., Pai et al., 2017), the number and type of sensors that can be installed on commercially available UAVs, along with UAV payloads, continues to expand. Given the ability of UAVs to capture high resolution data over large areas, we expect that this is an area of future research opportunities.

5.3. Future research opportunities

Using recent trends as presented above and our own insights, here we outline future opportunities in GW-SW interactions research. Although the fundamentals of hydrology and hydrogeology are largely unchanged since the 1970 s, for example, the vast majority of the *Groundwater* textbook by Freeze and Cherry (1979) remains current, the many disciplines that now participate in GW-SW interactions research have led to a proliferation of techniques, technologies and approaches. Indeed, over 20 years ago, Schwartz and Ibaraki (2001) suggested that in the field of hydrogeology "*the number of truly impactful problems has dwindled to just a few.*" However, through GW-SW interactions research, hydrogeology may still provide truly impactful research opportunities. The increased size of the GW-SW field since 2001 (Figs. 3, 5) could have led to issues of citation dilution as discussed by Schwartz and Ibaraki (2001). Nonetheless, many knowledge gaps in GW-SW interaction research remain. Preferential flow pathways and heterogeneities in aquifers and bed materials continue to pose a challenge to quantifying or upscaling GW-SW interactions (e.g., Claude et al., 2019). The role that GW-SW interactions can play in removing contaminants is an area of active research (e.g., Ping et al. 2021). Climate change and groundwater extraction will continue to alter GW-SW systems (e.g., Benz et al., 2024; Petpongpan et al., 2022), potentially driving changes in stream drying that affect management (e.g., Walker et al., 2021). Similarly, sea-level rise will likely continue to pose problems in the coastal zone (e.g., Martínez-Pérez et al., 2022) by driving saltwater intrusion and potentially altering the geochemistry of coastal aquifers and receiving waters. This is clearly a partial list of challenges; and additional GW-SW interactions research challenges will likely develop in the future. Field-based research using existing and new techniques, sensing tools, and interpretive methods could be used to address these challenges. The discussion below outlines areas that we believe show promise as future directions in GW-SW interactions science.

5.3.1. Drones and uncrewed vehicles

Examples of recently developed commercial UAV sensors with applications in GW-SW interactions studies include thermal infrared, Light Detection and Ranging (LiDAR; e.g., Bandini et al., 2017), multi- and hyper-spectral imaging (e.g., Pai et al., 2017), electromagnetic, ground-penetrating radar, and remote sampling of surface water Straight et al. (2021). Many of the signals measured with UAV instruments could be used to parameterise models (e.g., topography for integrated surface–subsurface models) and detecting and characterising the distinctive features and conditions of groundwater discharge zones (e.g., temperature, biogeochemistry, wetted channel length). For example, Pai et al. (2017) used drone-based Normalised Difference Vegetation Index to explore river corridor vegetation health as related to subsurface flow through meanders in semi-arid terrain, while Dugdale et al. (2019) used UAV-based vegetation height metrics to parameterize stream-temperature models. Two reviews of UAV as applied to hydrologic systems broadly can be found in Vélez-Nicolás et al. (2021) and Acharya et al. (2021). High-resolution visual imagery from UAVs may also be used to detect zones of focused groundwater discharge in colder regions that manifest as ice-free areas in rivers and streams during winter months, a phenomenon that has been demonstrated at lower resolution from satellite imagery (O'Sullivan et al., 2019). This list of sensors, many of which can now be purchased commercially, include several geophysical instruments that enable hydrogeophysical studies of GW-SW interactions. We believe that the high-resolution, georeferenced data that can be collected with these UAVs sensors has the potential to be transformative for mapping and modelling GW-SW interactions.

5.3.2. Scaling with the aid of remote sensing

Stream reach-scale (a few km or shorter) GW-SW field investigations dominate the literature but are universally challenged in providing system-scale (catchment to basin) information of use to water-resource managers. Near-surface geophysical methods provide spatial continuity and hydrogeological context for point data (e.g., see Binley et al., 2015; McLachlan et al., 2017), but they are rarely collected at scales beyond reaches and transects, with some exceptions (e.g., Briggs et al., 2022; Lane et al., 2020). In contrast, data describing processes of GW-SW interactions collected by occupied aircraft and satellites are being paired with emerging AI-based analyses to push the spatial limitations of ground-based surveys. For example, high-resolution hyperspectral data acquired by occupied aircraft offer temporal snapshots of vegetation type and health (Chadwick et al., 2020), which is influenced by GW-SW exchange in more arid environments and can indicate controlling hydrologic processes (Meyers et al., 2021). Thermal infrared data are now routinely collected by aircraft to map zones of groundwater discharge and thermal heterogeneity across all surface water types (Steel et al., 2017). Airborne electromagnetic imaging (AEM) data can be used to locate zones of surface water-groundwater connectivity at basin scales when either surface or groundwater is saline (Ball et al., 2015). However, occupied aircraft campaigns are costly and not often repeated at the timescales of seasonal change.

Satellite-based data, such as those from the Landsat satellite (U.S. Geological Survey, 2024b), provide global data every few weeks going back decades and are often freely available. Analysis products can indicate surface water inundation extent (Jones, 2019) and identify wetlands influenced by groundwater extraction (Heintzman et al., 2017). Landsat and AEM data have been combined to understand the impact of shallow permafrost thaw and arctic lake extent due to changes in lake-groundwater exchange (Jepsen et al., 2013; Rey et al., 2019). Groundwater discharge has been mapped using satellite thermal infrared data at regional scales in terrestrial (Sass et al., 2014) and ocean (Jou-Claus et al., 2021) environments. Although many surface water features are not currently resolvable due to the coarse spatial resolution (30–100 m pixels) and reduced accuracy of thermal infrared data due to edge effects, several higher-resolution commercial thermal infrared data sets are expected to become available in the coming years. New data types such as Surface Water and Ocean Topography (e.g., Altenau et al., 2021) are being made broadly available and have widespread applicability for estimating hydraulic gradients between surface and groundwater when paired with water-table elevations. New processing algorithms to infer large-scale algal blooms driven by the exchange of nutrient rich groundwater from satellite spectral imaging are allowing hindcasting of how such blooms have changed in timing and extent using publicly available time-series data (e.g., Cheng et al., 2020). Finally, remote sensing of river discharge from drones, occupied aircraft, and satellite platforms is becoming more accurate (Gleason and Durand, 2020), creating the potential for large-scale analysis of river gains and losses in remote areas across seasons. The citizens of many countries have made a collective investment in satellite-based remote sensing implemented by various governments, and the resultant publicly available data provide opportunities to inform GW-SW interactions science at management-relevant scales across the globe.

5.3.3. *Real-time monitoring networks, low-cost sensors and application of newer tracers*

The establishment and growth of real-time monitoring networks for groundwater and surface water is a recent development that can enable informed, real-time decision making for water-resources management (Zhou et al., 2018). Although commercial options for such real-time systems can be cost prohibitive for procurement and data management, the growth of "do-it-yourself" Internet-of-Things technologies and controllers (e.g., Arduino, Raspberry Pi) has led to the emergence of low-cost, often real-time monitoring of water levels, temperature and water quality that may enable more high-resolution or large-scale monitoring of GW-SW interactions because the low cost enables scalability (e.g., Calderwood et al., 2020; Drage and Kennedy, 2020; Espinoza Ortiz et al., 2023). The widespread use of real-time data can provide multiple benefits, including the potential for near-real-time numerical modelling. The availability of new wireless communications options, including Starlink, can also allow the use of real-time data to be measured in areas that previously did not have access to sufficient internet and phone-based services (e.g., Dinis et al., 2022).

The use of tracers has been a mainstay in the hydrological sciences. The wide array of existing approaches will likely continue to inform GW-SW interactions. The recently developed ability to measure noble gas concentrations in situ (e.g., Brennwald et al., 2016) is still in its relatively initial stages, though it is well suited for 'Lagrangian'-type continuous surface-water parameter surveys collected at ambient streamflow velocity from watercraft (e.g., Hensley et al., 2020). The rise of DNA-based tracing techniques (e.g., Pang et al., 2020) also shows promise to inform GW-SW interactions. With the increasing array of chemicals in use, new environmental tracers may arise, as was the case with chlorofluorocarbons (e.g., Hendlin, 2021). These approaches, amongst others, will expand the ability to inform various GW-SW interactions and associated processes. Future research could use these existing techniques and develop new tracing techniques. A continuing challenge will be to develop approaches that can be used to upscale the often point or local-scale investigations over which tracer studies are often applied.

5.3.4. *Flow paths and contaminants*

There are a wide range of contaminants that occur at the GW-SW interface and are receiving increased research attention (e.g., microplastics, PFAS, TrOCs, pharmaceutical products, and pathogens, amongst others). Although research examining the medical effects of the human exposure to some contaminants (e.g., PFAS, microplastics) there is in its preliminary stages, documenting the prevalence and extent of these contaminants in GW-SW systems is becoming increasingly important for informing management activities. Microplastics and PFAS are now ubiquitous in the environment; microplastics have been found in groundwater via karst/cave systems (Balestra and Bellopede, 2022; Panno et al., 2019), while PFAS chemicals have been found most everywhere (Johnson et al., 2022). Although the class of PFAS compounds is often referred to as 'forever chemicals', important reactions of precursors have recently been documented at the GW-SW interface (e.g., Tokranov et al., 2021). Challenges remain in understanding contaminant flow pathways in GW-SW systems due to heterogeneities in the subsurface, dominance of preferential flow processes, and the complex potential combination of biotic and abiotic chemical reactions that tend to occur in interface sediments. Understanding the surface or subsurface flow paths that contaminants take from source to receptacle and how those pathways are influenced by GW-SW exchange has long-term implications for human and ecosystem health given the 'legacy' effects of contaminants in groundwater systems (Basu et al., 2022b).

5.3.5. *Knowledge transfer across disciplines*

This review has highlighted the increasingly multi-disciplinary nature of GW-SW interactions research (e.g., Figs. 5 and 8). International collaborations on multi-disciplinary projects spur innovations that quickly advance the science of GW-SW interactions despite the challenges posed by the differences in language among researchers (Singha et al., 2024). Multidisciplinary collaborations provide opportunities for the translation of knowledge across disciplines and are often required to address complex research questions. This point has been made elsewhere for GW-SW systems, with suggestions for increased collaboration among hydrological scientists and ecologists (e.g., Humphreys, 2009), climate scientists (e.g., Hannah et al., 2007) and biogeochemists (e.g., Smith et al., 2008), and a wide range of other disciplines including non-scientific, disciplines. With increased pressure on water resources from contamination, overextraction, and climate change, we reiterate that ongoing collaborations can help promote existing knowledge transfer across disciplines. We suggest that GW-SW interactions is a natural topic for such collaborations because this topic spans the surface and subsurface aquatic environments that are often studied in disciplinary silos.

5.3.6. *The future of numerical modelling and AI*

Advances in computational power have outpaced our ability to measure field parameters at appropriate spatiotemporal resolution to characterise many processes relevant to GW-SW interactions. As a result, process-based models still use simplified representations of hydrogeological systems, particularly for subsurface properties (Thornton et al., 2022). Brunner and Simmons (2012) highlight the benefit of having models with a wide range of functionality, that can be used where the necessary data are available. Despite the challenges, large-scale (e.g., continental) models that include groundwater and surface-water processes in some manner are available (Cosgrove et al., 2024; Maxwell et al., 2015; Vaze et al., 2013) or are under development (Aquanty, 2024). Given the challenges in measuring model parameters, Beven (2018) highlights that using models to test hypotheses remains a valuable pursuit. For example, studies exist where all models tested were ultimately rejected due to poor predictive abilities (Choi and Beven, 2007; Dean et al., 2009). This testing of multiple conceptual models or the use of heterogenous realisations of hydraulic properties are approaches often used in hydrogeological investigations (e.g., Enemark et al., 2019). Although ultimately more computationally intensive, hypothesis testing can be informative about what is and is not, known about the region of interest.

Artificial Intelligence (AI) approaches (including a broad range of machine-learning techniques) are being used to assist the parameterisation of complex process-based numerical models. For example, Barclay et al. (2023) used guided deep-learning approaches to inform river-temperature models, Wunsch et al. (2022) conducted a national assessment of groundwater storage under different climate scenarios, and Yang et al. (2020) showed that model predictions of daily streamflow improved after using synthetic datasets and machine-learning approaches. Neural networks, deep learning, or unsupervised algorithms have also been used to assess groundwater quality; however, the majority of studies focus on a narrow band of chemical compounds such as nitrate, which accounts for nearly one half the studies (Haggerty et al., 2023). Unsupervised machine learning has also been used to cluster inverted electrical resistivity data to map biogeochemically important regions in a hyporheic system (Singley et al., 2022). These examples highlight data or analysis gaps in the types of field observations that could be filled to more fully understand GW-SW interactions. Where additional data can be collected, they should. Otherwise, the use of machine learning and AI approaches to address data gaps has already shown to be a possible approach to assist the understanding of GW-SW systems.

Just as some are raising the possibility that AI will be the end of computer programming as we know it (e.g., Welsh, 2023), we emphasise here that although numerical models will likely continue to be an important component of GW-SW interactions research, how numerical models will be implemented and applied in the future is uncertain in the face of rapidly developing AI approaches. Regardless of the exact approach to running numerical models, future modelling efforts that inform GW-SW interactions on appropriate scales could be used to inform water-resources management. Numerous important processes have been elucidated through decades of GW-SW interactions research, but predictive power and precision related to management-relevant themes, such as nutrient fate and transport above the reach scale, remains relatively low. This could mean that there is still a lack of process understanding and/or the existing models do not include the complexity of processes. Broad overviews of potential AI applications provide insights into AI opportunities in the hydrological sciences (e.g., Foroumandi et al., 2023; Halloran et al., 2023; Irvine et al., 2023). However, we are in the early stages of large-scale AI applications, and we hypothesise that AI will continue to have a wide-reaching influence on future research, across all disciplines.

5.3.7. *Managing GW-SW systems*

Ultimately, measured, modelled, and interpreted data are needed to understand hydrological systems and facilitate water-resources management. With the increased water demands to sustain human populations, agriculture, and energy production paired with the prevalence of large-scale contamination of many water resources, developing more effective management regimes for GW-SW systems is crucial (Gorelick and Zheng, 2015). The 2023 U.S. Supreme Court decision that the U.S. Clean Water Act only holds in continuously flowing surface water bodies has implications for interactions of groundwater and surface water systems (e.g., US EPA, 2023). Although the limitations and challenges in managing groundwater have been identified including in how to set effective trigger levels to minimise localised impacts (e.g., Rohde et al., 2024; Werner et al., 2011), broad management frameworks that acknowledge GW-SW as a single connected system are lagging despite longstanding calls for conjunctive management (e.g., Winter et al., 1998). Acknowledging the dynamic relationship between groundwater and surface water when determining volume extraction limits could help inform management strategies that protect ecosystems and sustain groundwater and surface water systems. Science-based allocation limits with a two-way process between scientists and managers could help ensure that sufficient system knowledge is available to support and inform management activities.

With the potential long lag time between groundwater systems and discharges to inland and coastal waters, developing a more holistic approach that acknowledges groundwater as a resource and a conduit for transporting water and contaminants into terrestrial and marine environments could inform management decisions The recently proposed 'Source-to-Sea' approach combines elements of the holistic management approaches of Integrated Water Resources Management and Integrated Coastal Management (Granit et al., 2017). These management approaches consider the interconnectivity of processes in hydrological and/or coastal systems. However, Source-to-Sea management approaches do not explicitly consider groundwater flow paths and the contaminants that they could transport (Granit et al., 2017; Michels-Brito et al., 2023). A new approach that views terrestrial, freshwater, and marine systems as a continuum (Fig. 1) rather than discrete segments could result in a more effective management framework.

Water-resources management is a complex process incorporating stakeholder views, and potential ecological disturbances and water extraction to support agriculture, industry, and town water supplies. There are multiple management approaches that provide opportunities to achieve this goal. For example, adaptive management, an approach that emphasises structured decision-making and uncertainty reduction (Williams et al., 2009), is increasingly cited in groundwater planning (Rohde et al., 2017). This approach involves the iterative integration of new knowledge through targeted monitoring to achieve desired outcomes (Thomann et al., 2022). Continuous reassessment and refinement of management actions via targeted monitoring improve the effectiveness of management actions over time (Thomann et al., 2020). Participatory management approaches (Ocampo-Melgar et al., 2022) can help involve stakeholders in solving complex problems. With many aggravated conflicts over water (Gleick and Shimabuku, 2023), shifting from top-down to participatory decision-making can help address the common issue of water-resources management decisions often being disconnected from their social context (Huggins et al., 2023).

6. Concluding remarks

Interactions between groundwater and surface water occur in a range of settings from headwater streams to coastlines and play a critical role in controlling many physical and biogeochemical processes. Given the broad range of processes that influence and are influenced by GW-SW interactions, the growth in research interest in GW-SW interactions in terms of both the number of research outputs and contributing disciplines is not at all surprising. This multidisciplinarity in research should continue to inform our understanding of important parameters and processes that control GW-SW interactions. While there has been a notable volume of research into the complex interactions between surface water and groundwater, there remains much to do to integrate the learnings from the many disciplines that investigate these processes. The papers that we identified as having potential to have future impact on GW-SW interactions research (Table 3) focused on understanding processes using field measurements and/or numerical modelling. Much of the past research focus has been at relatively small scale, i.e., bedform to reach scale, with impediments in upscaling those findings in ways that could benefit resource managers of aquatic systems. Growing populations, continued economic development, and effects of climate change demonstrate the utility of approaches that upscale available local-scale knowledge. Effective management, mitigation, and adaptation strategies could help address these challenges to provide water for communities and the environment. Thus, studying and understanding relevant processes in GW-SW systems could help generate knowledge that could be used to inform this conversation. The emergence of new mapping and monitoring technologies, tracer techniques and modelling capacity provide new opportunities to inform strategies to address the societal and technical challenge of monitoring, predicting, and managing GW-SW exchanges.

CRediT authorship contribution statement

Dylan J. Irvine: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kamini Singha:** Writing – review & editing, Writing – original draft. **Barret L. Kurylyk:** Writing – review & editing, Writing – original draft. **Martin A. Briggs:** Writing – review & editing, Writing – original draft. **Yakub Sebastian:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Douglas R. Tait:** Writing – review & editing, Writing – original draft. **Ashley M. Helton:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

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Data availability

Data available via FigShare

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Appendix A. Supplementary data

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A review of modelling of groundwater-surface water interactions in arid/semi-arid floodplains

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Abstract: Floodplains and their wetlands are extremely important centres of biodiversity due to their ability to support higher amounts of biomass than surrounding upland areas. This is as a result of flooding which provides greater availability of water and more dynamic nutrient cycling. In arid and semi-arid regions, where evapotranspiration is often much greater than rainfall, this additional source of water (and nutrients) creates ecological oases for many biota in what would otherwise be a harsh environment. Floodplains also have a very important hydrogeological role in that they are the interface zone between streams and groundwater systems where exchange of water and solutes occur between these systems. The groundwater systems of this interface zone are complex and dynamic with processes such as bank storage exchange, hyporheic zone exchange, overbank inundation and recharge, evapotranspiration and groundwater pumping needing to be accounted for in water balances. While modelling of groundwater-surface water interactions in floodplains, from either water resource availability or ecological sustainability perspectives, is far from a mature area of science, there have been significant advances over the last 15 years, particularly in the area of spatial modelling. In this paper, we summarise the advances that have been made in saturated zone, unsaturated zone and combined modelling methods.

Modelling has progressed from relatively simple 1D and 2D analytical and empirical approaches to highly sophisticated 3D spatially distributed integrated modelling systems, with the advances mirroring the vast increases in desktop computing power over that time. In our view, future advances in this discipline are not so much limited by either computing power or solution methods, but rather by the availability of suitable data needed to parameterize, calibrate and validate the current-day models. As pointed out by Silberstein (2003), any model is only as good as the data upon which it is based and has been tested. Whilst calibration of very detailed process models has been possible for small (sub-reach scale) study areas, success has been limited at the reach, catchment and regional scales. However, new large-scale satellite/airborne data acquisition techniques are showing great promise, with some of the recent studies illustrating their value in model parameterization, calibration and validation. Because of severe data limitations in many areas, simple analytical models are still an attractive option in many cases as they generally only have a small number of parameters that require calibration. They can also be easily incorporated into publically available (i.e. inexpensive non-proprietary) GIS and other software frameworks. In our view, use of more sophisticated numerical models are only valid in data-rich situations or when used as research tools to study fundamental processes and parameter dependencies. At best, most detailed models will be only be usable for management as forecasting/what-if tools, and should not be considered as scenario prediction models unless they have been thoroughly calibrated and validated.

Keywords: *Groundwater, surface water, interaction, floodplain, modelling*

1. INTRODUCTION

Approximately one third of the world's land area is comprised of arid/semi-arid regions (Rogers, 1981). Extreme climatic variability and subsequent hydrological fluctuations are typical in these regions. The climatic variability occurs seasonally, inter-annually and on longer time frames. Consequently, arid/semi-arid areas are subjected to frequent and severe droughts and infrequent but significant floods. Climate variability and subsequent fluctuating hydrology are key drivers of ecology in arid/semi-arid environments.

To overcome the highly variable stream flow in arid/semi-arid areas, rivers have been regulated to provide year-round water supplies, transportation, waste assimilation, recreation and electricity generation. River regulation has often had profound hydrological and ecological side-effects on the rivers themselves and their adjacent floodplains (Jolly, 1996). Floodplains generally support higher amounts of biomass, have greater primary production and more dynamic nutrient cycling than surrounding upland areas. This is particularly the case in arid/semi-arid areas where potential evapotranspiration is greater than rainfall for most months and so flooding provides an additional source of water not available to non-floodplain areas (Hollis, 1990). Floodplains often also have an important hydrogeological role as the interface zone between streams and groundwater systems where exchange of water and solutes occur. Groundwater systems of this zone are complex and dynamic, with processes such as hyporheic exchange, bank storage exchange, overbank inundation, evapotranspiration and groundwater pumping needing to be accounted for in water balances (see Figure 1 for examples of some of these processes).

There have been significant advances over the last 15 years in the modelling of groundwater-surface water interactions in floodplains (water and solutes), both from a water resource availability perspective and from an ecological sustainability viewpoint. It is timely to take stock of what has been achieved to predict future directions. This short paper summarises the advances made and discusses some of the data issues which are limiting further progress in this area. The paper builds on the findings of a recent review of groundwater-surface water interactions in arid/semi-arid wetlands (Jolly et al., 2008) by expanding the scope to floodplains in general and by focusing specifically on modelling approaches. We describe saturated zone, unsaturated zone and combined methods.

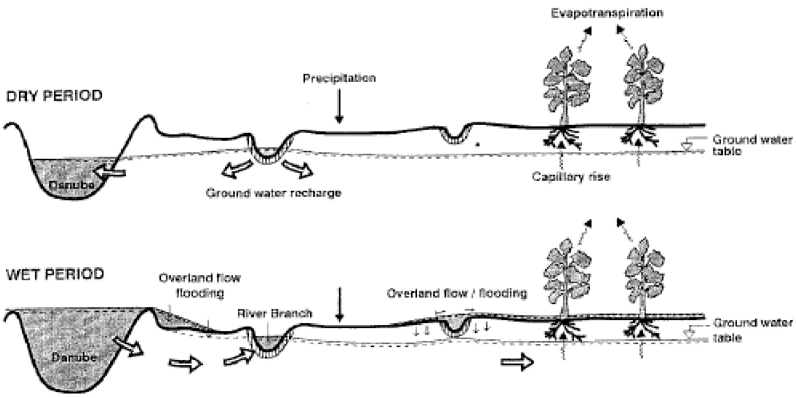

Figure 1. Important floodplain hydrology processes and their interactions (from Refsgaard et al., 1998).

2. SATURATED ZONE METHODS

2.1. Bank storage

By the early 1990's considerable literature had been developed on analytical solutions to bank storage interactions (see extensive review by Rassam and Werner, 2008). The first published application of these solutions to a arid/semi-arid floodplain situation was the study of Jolly et al. (1994) which developed a 2D analytical solution for the prediction of groundwater heads beneath two 2 km long cross-sections of a floodplain which was controlled by head fluctuations of streams on either side of the floodplain. This relatively simple model provided good transient predictions of groundwater head during a flood event on the Chowilla floodplain in south-eastern Australia. The main shortcomings of the approach were (i) that it assumed that Dupuit-Forchheimer conditions hold (i.e. horizontal groundwater flow); (ii) it only predicted groundwater heads and not fluxes; and (iii) it did not apply to situations where there was vertical recharge or discharge within the floodplain (i.e. only the effects of bank storage were modelled).

Whiting and Pomeranets (1997) also developed a general 2D model of bank storage (WaTab2D). This model used a finite element approach that enabled representation of the seepage faces that form on the sides of stream channels, non-symmetrical valleys, non-symmetrical channel banks, non-uniform hydraulic geometry (i.e. Dupuit-Forchheimer conditions do not need to hold), and non-zero boundary fluxes. The un-calibrated model was used to show that the total volume of water released from bank storage is nearly proportional to the width of the floodplain, the height of the bank, and the specific yield of the aquifer. It was also used to show that the duration over which water is released from bank storage (i) increases with floodplain width and decreases with hydraulic conductivity; (ii) the rate of release decreases in an exponential-like manner; and (iii) can occur over time periods ranging from days (in gravels) to years (in clays).

The most recent work on 2D floodplain bank storage methods is the analytical model of Knight and Rassam (2007). This is a significant improvement on previous analytical methods in that the stream head fluctuations can be a random time series (described using basis splines) rather than having to be represented in functional form or as a convolution interval which must be evaluated numerically. The value of using analytical approaches such as this is that they can be easily incorporated into geographical information system (GIS) models. For example, Rassam et al. (2008) used this new method within a GIS framework to study the nitrate attenuation potential of riparian zones in the large (60,000 ha) Maroochy catchment in eastern Australia (note that this case study was in a sub-tropical area, however the method has application to arid/semi-arid areas). This approach is also being employed in a new analytical/empirical floodplain model presently being developed by the eWater Cooperative Research Centre (see paper by Rassam et al., 2009).

2.2. Overbank inundation

The most notable modelling of overbank inundation in a system which has remained relatively natural is the recent studies of the very large (1,200,000 ha) Okavango Delta in Botswana. Bauer et al. (2004) showed that transpiration from arid/semi-arid floodplains such as the Delta can be significant in situations where water tables are shallow (< 5 m below ground) as floodplain vegetation can use groundwater as a supplementary water supply in dry periods between floods. This, along with evaporation from bare soils, can lead to accumulation of salt in plant root zones and in the underlying groundwater. Overbank flooding can mitigate these accumulations of salt. Wolski et al. (2006) developed a GIS-based hydrological model of the Delta which was able to establish an overall water budget and was used to map areas that are inundated from floods. Bauer et al. (2006a) carried out coupled 3D groundwater flow and salinity transport modelling of the 10,800 ha Shashe River Valley on the fringe of the Delta using a modified version of the density-dependent SEAWAT model (Guo and Langevin, 2002). In this valley, a fresh groundwater lens had developed naturally over time due to annual flooding, but was being heavily exploited for domestic water supply and by riparian vegetation, leading to declines in groundwater levels and deterioration of water quality due to ingress of saline groundwater from adjacent aquifers. The modelling was used to gain an understanding of the complex interactions, including the interdependence of groundwater salinity and riparian vegetation transpiration. The study successfully reproduced the development of the groundwater lens and recent decline in piezometric heads, as well as explaining the old age of the saline groundwater surrounding the lens. Zimmermann et al. (2006) investigated groundwater flow and salt transport dynamics below an evaporation-dominated island in the Delta with 2D density-dependent simulations using three different numerical models. The simulation results supported geophysical observations reported in Bauer et al. (2004) of density fingering (caused by downward convection of saline water) in the groundwater beneath the island. They also showed that these density effects may be entirely overridden by lateral flow if islands are imbedded in a sufficiently transmissive aquifer within a high regional hydraulic gradient. Wolski and Savenije (2006) also studied the dynamics of floodplain-island groundwater flow in the Delta, but employed more traditional MODFLOW modelling techniques. They found that floodplain-island groundwater flow was in general very dynamic, was driven by island evaporation and transpiration, and that regular flooding was required to replenish groundwater stores. They concluded that a prolonged reduction in the duration or level of a flood could result in depletion of the groundwater storage with negative effects on the riparian vegetation.

In many floodplain systems, river regulation by weirs/locks and upstream storages has led to raised water tables beneath floodplains and reduced frequency and duration of overbank flooding. Water tables beneath floodplains can also be raised by increased groundwater inflows into floodplains from adjacent areas due to changes in land management such as the development of irrigation areas. The increased evapotranspiration and decreased recharge that can result can lead to net accumulation of salt in plant root zones and consequent floodplain vegetation dieback (Jolly, 1996). Doble et al. (2006) used relationships for evapotranspiration response to groundwater depth and salt concentration, within the MODFLOW-2000 framework, to successfully model spatial patterns of groundwater flux and salt accumulation within a small (500 ha) floodplain in south-eastern Australia (Clarks Floodplain). To more accurately model the recharge and evapotranspiration processes in this floodplain environment, where the boundaries between recharging and nonrecharging cells change with time, Doble et al. (2009) modified the MODFLOW-2000 recharge (RCH) and segmented evapotranspiration (ETS) packages to produce a recharge-discharge function (CRD) that allows groundwater flux to be represented as a continuous process, dependent on water table depth.

Hyporheic exchange is the rapid movement of water from the stream channel into and out of the surface depths of the alluvial aquifer over short (sub-reach) distances. The importance of hyporheic exchange is that it keeps surface water in close contact with chemically reactive constituents and microbial colonies in the stream bed, thus enhancing biogeochemical reactions that influence downstream water quality and ecosystems (Harvey and Wagner, 2000). Over the last decade, there has been some progress in modeling these fine scale processes. The modeling has either been very site specific and based on finely-gridded groundwater models such as MODFLOW (e.g. Wroblicky et al., 1998; Poole et al., 2008) or has involved the development of analytical, numerical and/or statistical approaches to help understand some of the fundamental water and solute exchange processes (e.g. Qian et al., 2008;. Boano et al., 2008). Research on hyporheic processes in general is a very active area of current research.

3. UNSATURATED ZONE METHODS

As described above, evapotranspiration from floodplains can result in accumulation of salt in plant root zones which can be leached back into the groundwater system by overbank floods. Slavich et al. (1999a) modelled soil salt accumulation/leaching processes at 2 sites in the Chowilla floodplain using a 1D soil-vegetation-atmosphere-transfer model (WAVES) to assess possible management options such as increasing flooding frequency by release of water from upstream storages and groundwater pumping to lower the water table. Whilst the modelling was successful, the authors recommended that the management options needed to be evaluated further at the floodplain scale to be useful for management. Slavich (1999b) then developed a salinity index (WINDS-Index), related to vegetation health, which could potentially be used in a GIS framework to evaluate management options at the floodplain scale. The approach utilised a simple 1D analytical root zone salt and water balance model which represented the salinisation process as a moving salt front. The dominant features of the more detailed WAVES simulations were adequately reproduced, and the WINDS-Index was found to be strongly dependent on the relative flood inundation time (the ratio of the duration of inundation to the duration between floods) of successive flood events. Overton et al. (2006) then implemented the WINDS-Index approach spatially in a GIS framework, tested its predictions against vegetation health mapping, and successfully used it to assess a wide range of potential management options aimed at improving the vegetation health of the large (17,400 ha) Chowilla floodplain.

4. COMBINED SATURATED AND UNSATURATED ZONE METHODS

To account for variably saturated conditions within bank storage, and the effects of density due to large salinity contrasts between stream water and groundwater, Jolly et al. (1998) applied a variable density flow and solute transport model (SUTRA; Voss, 1984) to a 4 km long cross-section of the Chowilla floodplain. The model was used to assess the importance of overbank floods in the transport of salt from the floodplain groundwater system to the lower River Murray system. The simulations showed that the mixing of flood water and saline groundwater within bank storage could explain short-term (<12 months) salt load recessions, but the observed long term (12-24 months) salt load recessions were due to the groundwater impacts of localised recharge from overbank floods at some locations on the floodplain.

To study the environmental impacts of a hydropower scheme in the 130 km long Danubian Lowland in eastern Europe, Refsgaard et al. (1998) developed an integrated modelling system comprised of catchment (MIKE SHE; Refsgaard and Storm, 1995), river (MIKE 11 and MIKE 21; Havno et al., 1995 and DHI, 1995) and unsaturated zone (DAISY; Hansen et al., 1991) models. This coupling allowed detailed modelling of the dynamic hydrological regime of this area which captured the crucial links and feedback mechanisms between the various parts of the surface and sub-surface water regimes, in particular those of the floodplain. One of the issues with this study was that while it was possible to model a complex area such as this in great detail, and the individual models could generally be validated, only a few tests on the integrated model were possible. This highlights one of the key problems with very detailed process modelling; there are often insufficient data available to both parameterise the models and then calibrate and validate them.

Hammersmark et al. (2008) have also used MIKE SHE and MIKE 11 to model surface water-groundwater interactions, in this case to quantify the hydrological effects of stream restoration in a small (230 ha) montane meadow system in northern California. The system was small enough that sufficient data was collected to enable a very good calibration and validation of the models. As a result they were able to successfully evaluate the pre- and post- hydrological responses in the meadow to the 'pond and plug' restoration methods (alluvium excavated, forming ponds; excavated material used to plug incised channels; and smaller dimension channels restored to the floodplain surface level) commonly proposed for these systems.

Bauer et al. (2006b) developed a large-scale (1 km^2 grid) coupled 2D surface water-groundwater model to study the water balance of the entire Okavango Delta under a range of scenarios (increased water abstraction, development of upstream hydropower and irrigation schemes, channel dredging, local climatic change, local tectonic events). The model was comprised of components which simulate overland flow (based on a diffusive wave approximation of the 2D Saint-Venant equations), groundwater flow (based on a modified version of MODFLOW-96), and recharge and evapotranspiration through the unsaturated zone (using mass balance and an empirical relationship between evapotranspiration and water table depth). Due to a lack of site data, the model was not calibrated with point hydrographs but with pixel by pixel comparisons with flooding pattern time series derived from satellite imagery (151 images from 1972-2000). The authors cautioned that given the high uncertainty of both the calibrated and input parameters the model outputs could not be considered as predictions, rather they gave indications of the potential changes in flooding patterns.

There have also been extensive studies of a large (19,800 ha) floodplain of the Lower Havel River in northern Germany that have involved the development of the Integrated Modelling of Water Balance and Nutrient Dynamics (IWAN) modelling system (Krause and Bronstert, 2005, 2007; Krause et al., 2007a, 2007b). IWAN is comprised of the two way coupling (i.e. feedbacks in both directions) of the WASIM-ETH-I spatially distributed runoff generation and vertical soil water dynamics model (Schulla and Jasper, 1999) with MODFLOW-96. The most recent version of IWAN includes the SWIM (Krysanova et al., 2000) and MT3D (Zheng and Wang, 1999) models to simulate nitrate dynamics in both the unsaturated zone and groundwater (Krause et al., 2008). Use of IWAN to simulate the water balance of this floodplain indicated that interactions between groundwater and surface water controlled recharge dynamics in the floodplain and outweighed the influence of vertical percolation and root water uptake. While groundwater contributions represented only 1% of the annual total discharge of the river, in summer ~30% of the river flow was derived from groundwater discharge from the floodplain. Simulations of proposed land use and land management changes on the floodplain using IWAN showed that rates of nitrate leaching from the root zone into the groundwater and then the river could be reduced substantially, and this would have a large impact on river nitrate loads during low flow conditions.

5. CONCLUDING REMARKS

There have been very significant advances over the last 15 years in the modelling of groundwater-surface water-floodplain interactions. In addition to the studies described here there are at least a further 20 published studies focusing on temperate and tropical regions. Modelling has progressed from relatively simple 1D and 2D analytical and empirical approaches to highly sophisticated 3D spatially distributed integrated modelling systems, with advances mirroring the vast increases in desktop computing power over that time.

In our view future advances in this discipline are not so much limited by either computing power or solution methods, but rather by the availability of suitable data needed to parameterize, calibrate and validate the current-day models. As always, data collection is expensive, and therefore generally very difficult to fund. The scaling down of routine hydrological and hydrogeological monitoring in many jurisdictions has further exacerbated this problem. Many natural resource management policy makers and managers tend to consider process models as "silver bullets" without fully understanding that any model is only as good as the data upon which it is based and has been tested (Silberstein, 2003). Whilst calibration of very detailed process models has been possible for small (sub-reach scale) study areas (i.e. Hammersmark et al., 2008; Doble et al., 2006), success has been limited at the reach, catchment and regional scales. However, new large-scale satellite/airborne data acquisition techniques are showing great promise; the studies of Overton et al. (2006) and Bauer et al. (2006a) illustrate their value in model parameterization, calibration and validation.

In data-poor situations, simple analytical models are still an attractive option as they generally only have a small number of parameters that require calibration. They can also be easily incorporated into publically available (i.e. inexpensive non-proprietary) GIS and other software frameworks (e.g. Overton et al., 2006; Rassam et al., 2008, 2009). In our view, use of more sophisticated numerical models are only valid in data-rich situations or when used as research tools to study fundamental processes and parameter dependencies. At best, most detailed models will only be usable for management as forecasting/what-if tools, and should not be considered as scenario prediction models unless they have been thoroughly calibrated and validated.

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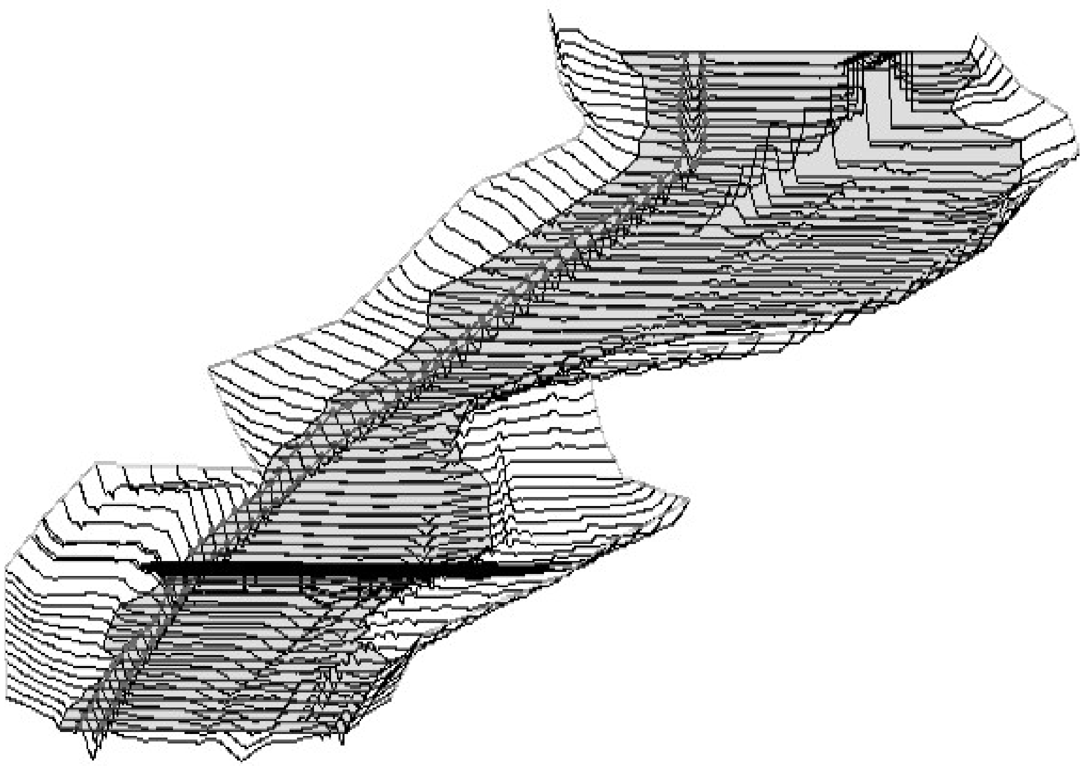

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4 THEORETICAL BASIS FOR ONE-DIMENSIONAL AND TWO-DIMENSIONAL HYDRODYNAMIC CALCULATIONS

This chapter describes the methodologies used in performing the one-dimensional (1D) steady flow and unsteady flow calculations, as well as the two-dimensional (2D) unsteady flow calculations within HEC-RAS. The basic equations are presented along with discussions of the various terms. Solution schemes for the various equations are described. Discussions are provided as to how the equations should be applied, as well as applicable limitations.

1D Steady Flow Water Surface Profiles

HEC-RAS is currently capable of performing 1D water surface profile calculations for steady gradually varied flow in natural or constructed channels. Subcritical, supercritical, and mixed flow regime water surface profiles can be calculated. Topics discussed in this section include: equations for basic profile calculations; cross section subdivision for conveyance calculations; composite Manning's n for the main channel; evaluation of the mean kinetic energy head (velocity weighting coefficient alpha); friction loss evaluation; contraction and expansion losses; computational procedure; critical depth determination; applications of the momentum equation; air entrainment in high velocity streams; and limitations of the steady flow model.

Equations for Basic Profile Calculations

Water surface profiles are computed from one cross section to the next by solving the Energy equation with an iterative procedure called the standard step method. The Energy equation is written as follows:

1)

$$Z_2 + Y_2 + \frac{\alpha_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{\alpha_1 V_1^2}{2g} + h_e$$

Symbol	Description	Units
Z_1, Z_2	elevation of the main channel inverts	
Y_1, Y_2	depth of water at cross sections	
V_1, V_2	average velocities (total discharge/ total flow area)	
a_1, a_2	velocity weighting coefficients	
g	gravitational acceleration	
h_e	energy head loss	

A diagram showing the terms of the energy equation is shown in the figure below.