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SMART Research: Toward Interdisciplinary River Science in Europe

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Interdisciplinary science is rapidly advancing to address complex human-environment interactions. River science aims to provide the methods and knowledge required to sustainably manage some of the planet's most important and vulnerable ecosystems; and there is a clear need for river managers and scientists to be trained within an interdisciplinary approach. However, despite the science community's recognition of the importance of interdisciplinary training, there are few studies examining interdisciplinary graduate programs, especially in science and engineering. Here we assess and reflect on the contribution of a 9-year European doctoral program in river science: 'Science for MAnagement of Rivers and their Tidal Systems' Erasmus Mundus Joint Doctorate (SMART EMJD). The program trained a new generation of 36 early career scientists under the supervision of 34 international experts from different disciplinary and interdisciplinary research fields focusing on river systems, aiming to transcend the boundaries between disciplines and between science and management. We analyzed the three core facets of the SMART program, namely: (1) interdisciplinarity, (2) internationalism, and (3) management-oriented science. We reviewed the contents of doctoral theses and publications and synthesized the outcomes of two questionnaire surveys conducted with doctoral candidates and supervisors. A high percentage of the scientific outputs (80%) were interdisciplinary. There was evidence of active collaboration between different teams of doctoral candidates and supervisors, in terms of joint publications (5 papers out of the 69 analyzed) but this was understandably quite limited given the other demands of the program. We found evidence to contradict the perception that interdisciplinarity is a barrier to career success as employment rates were high (97%) and achieved very soon after the defense, both in academia (50%) and the private/public sector (50%) with a strong international dimension. Despite management-oriented research being a limited (9%) portion of the ensemble of theses, employment in management was higher (22%). The SMART program also increased the network of international collaborations for doctoral candidates and supervisors. Reflections on doctoral training programs like SMART contribute to debates around research training and the career opportunities of interdisciplinary scientists.

Keywords: river science, doctoral training, interdisciplinary training, international collaboration and mobility, science for management

INTRODUCTION

Interdisciplinary research and training programs are pivotal to address the complex, multi-faceted environmental challenges we are facing. It requires various methods and approaches aligned to individual disciplines (Klein, 1990; Millar, 2013), and sustainable solutions arise through the interaction among disciplines (Kates et al., 2001; Borrego and Newswander, 2010). At the same time, interdisciplinary research requires humility, mutual respect, open-mindedness, and an ability to see things from different perspectives, which again may support creativity and 'thinking outside the box' to generate innovative solutions (Gardner, 2013). New insights and educational value can be gained (Andersen, 2016) when ways of learning and methods of a given discipline are exported to another one and sometimes knowledge and methods from different disciplines can be seamlessly merged, yielding a more holistic, integrated view (Wagner et al., 2011; Andersen, 2016; Power and Handley, 2017).

Today, the need for such a systemic and integrated view on environmental issues is well accepted. Many scientists have therefore welcomed the emergence of unconventional approaches that go beyond their own research areas, leading to rapidly developing interdisciplinary fields starting from hydroecology, ecohydrology, eco-hydromorphology and eco-geomorphology that extend beyond ecology, geomorphology, and hydrology, up to biomedical engineering and bioinformatics (Braun and Schubert, 2003; Porter and Rafols, 2009). River science is emerging as one such interdisciplinary research field because rivers are, fundamentally, complex physical, biological, chemical and socio-economic systems whose watersheds often cross multiple political and administrative boundaries (Thoms, 2005; Dollar et al., 2007). Three elements are critical to support a new paradigm and develop sustainable solutions: interdisciplinary working; international collaboration; management-oriented science.

The relevance of interdisciplinary research in river science has been increasingly recognized over the past two decades (e.g., Thoms and Parsons, 2002; Stallins, 2006; Post et al., 2007; Murray et al., 2008). Lack of interdisciplinarity limits the ability to predict (river) landscape response to human disturbance and climate change (e.g., Reinhardt et al., 2010), and the need for a deeper dialogue between geomorphologists, ecologists and hydraulic engineers is increasingly advocated as priorities to develop effective science for management (Vaughan et al., 2009) and in relation to broad and specific open scientific issues (Rice et al., 2010). Vugteveen et al. (2014) argue that river research needs to be more collaborative and integrated for it to become fully inter-disciplinary in nature. Therefore, we need integration of knowledge and methods across spatial (Thoms and Parsons, 2002) and temporal scales and from diverse disciplines including freshwater biology, limnology, geology, geomorphology, ecology, remote sensing, hydrology, hydraulics, engineering, sociology, economics, and history (Wotton and Wharton, 2006).

Over the last century, river systems have been fundamentally and, in many cases, irreversibly transformed through human interventions (e.g., dam construction, channelization, water abstraction, pollution, sediment mining) with acute and chronic impacts on their flow, sediment, and thermal regimes as well as on their biodiversity, ecosystem functions, and related services (Petts, 1984; Brookes, 1988; Kondolf, 1994; Nilsson et al., 2005; Grill et al., 2019). Partly less obvious, but not less concerning, are the impacts arising from climate change, land use alterations, and societal changes (e.g., artificial light at night, see Hölker et al., 2010) and these are posing enormous challenges to river science and management (Perkin et al., 2011; Gilvear et al., 2016; Reid et al., 2019; Stecca et al., 2019).

A better understanding of the interactions between humans and rivers and "Riverine landscapes as coupled socio-ecological systems" (6th Biennial Symposium of the International Society for River Science, ISRS 2019) is critical to mitigate adverse anthropogenic impacts and to sustainably manage these systems. A common framework and a common set of concepts is fundamental to facilitating effective collaboration and communication of knowledge and approaches between scientists, managers, and policy makers (Dollar et al., 2007). Scientific developments and evolving management trends are fundamentally intertwined (e.g., Graf, 1993) and explicit recognition of this legacy is essential to develop innovative solutions required to face the complex challenges posed by such coupled socio-ecological systems (e.g., Leuven et al., 2007). The individuals who form the scientific and decision-making communities and who work at the boundaries between them (Gieryn, 1995) are key to achieving these goals and real progress will come from co-researching and collaboration between researchers, river professionals, and policy makers (Vugteveen et al., 2014). Millar (2013) has called for greater examination of how interdisciplinarity impacts the research process and the need to begin with the researchers themselves. This paper contributes to the discussions around how we train river scientists of the future (**Figure 1**) so that they are equipped to: address the dynamics of river systems that are interdisciplinary by nature (Palmer et al., 2005), to acknowledge, draw from, and develop an international scientific knowledge system (Pinter et al., 2019), and to play an effective role at the boundary with policy and decision making (Cash et al., 2003), from local to global scales.

FIGURE 1 | Graphical concept of questions in river science being addressed collaboratively by international interdisciplinary teams of scientists.

Thus, the key question addressed with this study is in which way and to which extent an interdisciplinary doctoral program on river science can contribute to both (1) the scientific advancement in the respective research field, and (2) an improved training of the next generation of scientists and managers able to provide them the best tools to tackle the research questions and challenges in river science and management of the future. We specifically focus on the aforementioned key elements of interdisciplinary, management-oriented research, within an international dimension that is key to overcome a parochial approach still characterizing many river management practices worldwide (see Pinter et al., 2019) and that emerged at the same time as a key priority in doctoral education beyond continental boundaries (e.g., Bitusikova, 2009).

In our paper, we share the analysis and reflections from a 9-year doctoral training program, "Science for MAnagement of Rivers and their Tidal Systems" Erasmus Mundus Joint Doctorate, hereafter referred to as SMART EMJD. It was one of the 43 EMJD programs funded by the Education, Audiovisual, Cultural Executive Agency of the European Union (EACEA). Within the broad need to adapt education systems to the demands of the knowledge society, the EMJD action (2009–2013) had the strategic goal of developing structured and integrated cooperation to implement common doctoral programs leading to the award of mutually recognized joint doctorate degrees (European Commission, 2013). The program was born from the sustained collaboration between individual senior scientists (Bertoldi et al., 2009) affiliated to three European universities that set out to train a new generation of river scientists. Through 36 doctoral research projects, organized under three key themes (**Figure 2**), the aim of the program was to address knowledge gaps in river science by adopting a much more integrated, holistic, interdisciplinary approach (Vaughan et al., 2009) with teams comprised of researchers from different educational and disciplinary backgrounds and drawn from a wide range of countries. Such teams help overcome the dangers of a strong disciplinary focus (see Pickett et al., 1994) for example gaps in understanding at the interfaces between disciplines, and a parochial approach (see Pinter et al., 2019). Furthermore, the program aimed to foster co-researching and collaboration between scientists, river professionals, and policy makers throughout the project as a more effective way to ensure more relevant science and improved evidence-based decision-making in river management, something that is unlikely to be achieved through paper-based communication of research results alone (Vugteveen et al., 2014). We share our evaluation of the SMART EMJD program in relation to its three core facets (interdisciplinarity, internationalism, and management-oriented science) to encourage and inform future integrated education and research activities in river science and other interdisciplinary research fields.

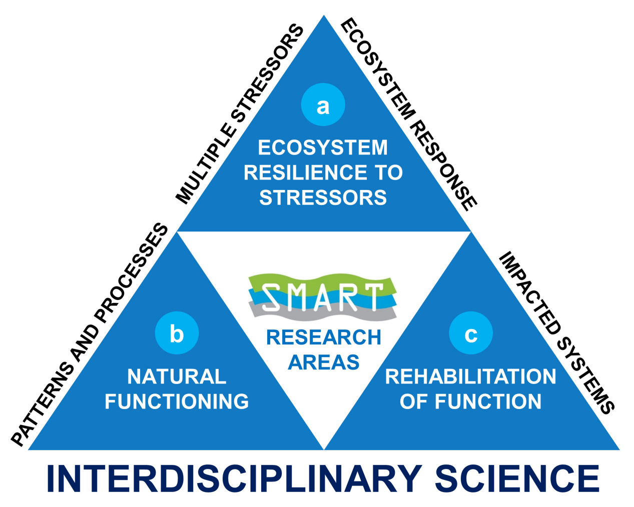


FIGURE 2 | The three research areas (a, b, and c) as defined within the SMART EMJD.

MATERIALS AND METHODS

Case Study: SMART EMJD

The SMART EMJD focused on core disciplines of the natural and engineering sciences relevant to the sustainable management of river systems, from their headwaters to their estuaries, including connected lakes and wetlands, and the interfaces between atmospheric, surface, and groundwater systems (Gurnell et al., 2016). Doctoral candidates were recruited from both EU and non-EU countries to carry out research in diverse teams that cross disciplinary, institutional, and geographic boundaries. International and interdisciplinary perspectives were further promoted through mandatory international mobility periods. The doctoral candidates were required to spend at least 6 months in another country (i.e., at the secondary institution) and 2 months with an associate partner.

Consequently, doctoral candidates were capable to adopt and apply a multidimensional, multi-scale holistic approach to river science. The multidimensional component enforced the consideration of multiple stressors, e.g., altered water/sediment flow and thermal regimes, and degraded ecological status from noise, light, and chemical pollution. It also helped advancing river research, which traditionally focused on a single scale, by covering a range of spatial and temporal scales. A holistic approach allowed for the integration of the complex, potentially synergistic and sometimes overlooked interactions among physical, chemical, and biological components in different river system settings.

A joint doctoral degree was awarded by the primary and secondary institutions to the SMART EMJD doctoral candidates after successful completion of their doctoral thesis with the thesis defense or viva-voce examination taking place at and following the regulations of the primary institution.

Lead Institutions and Associate Partners

Research training was delivered by three lead universities: The University of Trento, in close collaboration with the Edmund Mach Foundation in Italy; the Freie Universität Berlin, in close collaboration with the Leibniz-Institute of Freshwater

Ecology and Inland Fisheries (IGB) in Germany; and Queen Mary University of London in the UK. All three universities exhibited a history of successful research collaboration, and are engaged with practitioners in developing approaches to sustainably manage rivers and their tidal environments. Further institutions from multiple sectors in both EU and non-EU countries contributed to the program as Associate Partners (**Supplementary Table S1**), hosting doctoral candidates for at least 2 months with the aim to facilitate interactions with water policy-makers, river managers, and practitioners (i.e., facilitating transdisciplinary research).

SMART Doctoral Candidates

Doctoral candidates were selected from European and non-European countries following the Erasmus Mundus Program rules and selection was based on their written qualification, CV, personal statement, research proposal, and reference statements; followed by a face-to-face interview (primarily via Skype) with all shortlisted candidates. Funding was provided for five consecutive cohorts (5–10 candidates per cohort), starting in 2011. A total of 42 doctoral candidates, out of 378 eligible applicants, were finally selected (i.e., 11%); 36 candidates successfully completed their thesis (15 from EU and 21 non-EU countries). Of these candidates, 15 joined the University of Trento, 13 the Freie Universität Berlin, and 8 Queen Mary University of London as their primary institutions.

Research Areas

Doctoral research topics in the SMART EMJD were organized within three major research areas, (a) ecosystem resilience to stressors; (b) natural functioning; and (c) rehabilitation of function (**Figure 2**):

1. Ecosystem resilience to human and other stressors. Topics focused on the resilience of river-floodplain ecosystems to both natural and human-induced stressors. These included changes in hydrological connectivity, flow regulation by hydropower facilities, water abstraction, and changes in sediment supply, as well as more recent alterations such as artificial light at night or climate change related drivers.
2. The natural functioning of river-floodplain systems. Topics focused on the reciprocal linkages between physical processes and biota along river corridors, for improved understanding of their natural functioning. These linkages reflect feedbacks between flow, sediments, and vegetation, such as the ecosystem engineering capacity of plants. A special emphasis was given to drivers of bio-morphodynamics influencing the capacity of fluvial systems to self-regulate and attain good ecological status in both "reference" and "impacted" situations.
3. The potential to rehabilitate compromised functions in impacted systems. Topics aimed to evaluate the potential to support or rehabilitate desired functions in impacted river system by implementing eco-morphological measures such as river widening, habitat improvement (e.g., by introducing large wood), and other measures such as the implementation of ecological flows.

Data Collection and Data Analysis

Data were collected by reviewing scientific outputs (up to 31st March 2019) from the SMART EMJD doctoral candidates, and the reports produced by the SMART EMJD administration. Information on research articles was retrieved from Elsevier's Scopus, a database of peer-reviewed scientific literature. Three out of 69 published papers were not covered by Scopus at the time of the analysis. Therefore, they were excluded from further analyses based on the Scopus statistical tools. The numbers of cited references for these papers were retrieved from the Web of Science platform (Clarivate Analytics). The impact from the 69 research articles was assessed by the number of citations and the impact factor of the journal (retrieved from the journal's websites) at the time of the study (March 2019).

The data were explored in relation to the three key elements of the doctoral program: interdisciplinarity, internationalism, and management-oriented science. Two questionnaire surveys were sent to all SMART alumni and supervisors to ask about the overall perception of the program and of its effectiveness. The questionnaires are reported in the SI. The response rate was 69% from the doctoral candidates and 76% from the supervisors. The responses provided insights into the experiences gained through the doctoral program and contextualized the information emerging from the analyses of the scientific outputs.

Interdisciplinarity

There have been a wide range of definitions of interdisciplinary research (e.g., Klein, 1990, 1996; Becher and Trowler, 2001; National Academy of Sciences et al., 2005; Wagner et al., 2011). In this study, we adopted the definition of the National Academy of Sciences et al. (2005) as "*. . .a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice*." This definition has been widely adopted (Porter et al., 2006, Rafols and Meyer, 2008; Porter and Rafols, 2009; Wagner et al., 2011). We also adopted the addition proposed by Aboelela et al. (2007) of a requirement of perspectives and skills of the involved disciplines throughout multiple phases of the research process. These key criteria of researchers from different disciplinary backgrounds working in collaboration, with an integrated approach, toward an agreed common goal, and with on-going dialogue is what distinguishes interdisciplinarity from: multi-disciplinarity (*more than one discipline working on the same problem but with no real conversation*); pluri-disciplinarity (*disciplines interacting on the basis of work from other disciplines*); trans-disciplinarity (*the organization of interdisciplinary research by a grand unifying vision*) (see Klein, 1990), and cross-disciplinarity (*a generic, over-arching term for multi-, inter-, pluri- and transdisciplinary*) (Vugteveen et al., 2014).

In our study the criteria used for measuring interdisciplinarity were (1) number of fields/disciplines integrated in the research and (2) expertise of the participants. We considered three major components of river science: landforms, biota and water flow, as identified in earlier literature (e.g., Corenblit et al., 2007, see also D'Alpaos et al. (2016) for a short review of currently used terminology). A research "focus" was then defined by an integrative term that combined research disciplines into a single term (e.g., biogeomorphology), or two adjacent terms (e.g., light ecology). A percentage score was given to quantify the proportion of each doctoral thesis covered by a research focus and was computed as (1/n) × 100% for a thesis that covered n areas. The proportions were related to the core chapters reporting the substantive research results in the doctoral theses, where each chapter was assigned a main research focus according to its content. For example, if a thesis consisted of three research chapters of which two mainly focused on biomorphology and one on ecology, 66% would be given to biomorphology and 33% to ecology for the entire thesis. The main research focus of a chapter was usually described in the thesis, and if not, the author selected the most appropriate focus. The overall contribution of a research focus to the whole of the 36 theses was computed as the sum of each score for that focus weighted by the proportion of theses in which that focus was present.

For all SMART EMJD alumni and supervisors, a background check was conducted to characterize initial disciplinary and specialist fields. This was done by consulting sources such as CVs, personal and university webpages to ascertain postgraduate degree areas and/or reported work experience immediately prior to involvement in the SMART EMJD. The backgrounds of doctoral candidates were defined with reference to the three major research components for river science: "water flow," "biota" and "landforms," which have been labeled as "HYDRO," "ECO," and "GEO," respectively. Twenty-seven doctoral candidates were categorized within one of these fields, one was categorized in geomatics and eight had an interdisciplinary background combining two main areas. Although most supervisors were involved in collaborative research projects spanning different fields, an interdisciplinary background was assigned only to people for whom multiple research areas were equally important. The backgrounds of SMART EMJD alumni were compared with those of the supervisors and the interdisciplinary research areas of the doctoral theses to analyze the knowledge gained from interdisciplinary fields.

Internationalism

The international character of the program was analyzed through the nationalities of SMART EMJD applicants and doctoral candidates and the international collaboration established within the program. Internationalism was also quantified as the proportion of applicants and selected doctoral candidates recruited from 5 out of the 7 continents globally. These values were compared to the nationalities of applicants and selected doctoral candidates of all EMJDs for the year 2015 (including SMART), for which data were available on the funding agency website[1]. We further analyzed international collaboration during the program and relocation of the doctoral candidates after finishing the program, for example returning to their home country or moving to a new country.

[1] https://eacea.ec.europa.eu/erasmus-plus/library/scholarship-statistics_en

Management-Oriented Science

The doctoral theses were categorized according to the research areas defined in **Figure 2**. This analysis was undertaken by detailed screening of the theses to detect the main links to: (a) ecosystem resilience; (b) natural functioning; and (c) river management. Each thesis chapter was assigned to one or more areas and when more than one area was identified the percentage score was equally divided. The science for management domain was further analyzed through the responses to the surveys, and occupations of SMART EMJD alumni at the time of the survey.

RESULTS

Scientific Outputs and Impact

By the end of March 2019, SMART EMJD doctoral candidates had published 69 papers (59 first-authored, 15 co-authored papers), including five papers with two doctoral candidates as authors. Of the 69 papers, 50 were classified in Scopus as primary research articles; seven were classified as review/overviews articles, six as conference papers, and six as short papers. In total, 45% of all papers were accepted for publication before the candidates' defense date, corresponding to an average number of 0.9 papers per candidate, of which 71% were first-authored papers. This was lower than the average number of papers (1.9 papers per candidate before defense, 50% first-authored papers) of a reference group of 32 doctoral candidates enrolled at the same time as the SMART doctoral candidates in doctoral programs at the partner institutions. As expected, the number of papers related to the Ph.D. continued to grow after the defense.

Up to the end of March 2019, SMART EMJD papers were cited in total 831 times, by 709 different publications, including one paper that received 336 citations (Zarfl et al., 2015). There was no correlation between the number of citations of a specific paper and the impact factor of the respective journal (**Figure 3A**). As expected, the number of publications (and citations) increased with time (**Figure 3B**). The impact factor of the journals varied between 1.2 and 11.7 (mean: 4.2) (**Figure 3C**). On average, each SMART EMJD paper received 12 citations (median value: 6), excluding the article by Zarfl et al. (2015).

Interdisciplinarity in the SMART EMJD Research

Doctoral candidates and supervisors considered interdisciplinarity as a major asset of the SMART EMJD research program, indicated through the questionnaire. Among the doctoral candidate participants, 76% found it motivating to do research which included several disciplines and 76% agreed/fully agreed that their doctoral research was enriched by working with supervisors from different disciplinary backgrounds. While more than half of the doctoral candidates (52%) acknowledged that interdisciplinarity presented an extra challenge, 64% indicated that their research project could have been more interdisciplinary than it actually was. Furthermore, 80% stated that the interdisciplinary nature of the SMART EMJD has improved their career options and 92% stated that the program has improved their ability to work in an interdisciplinary context.

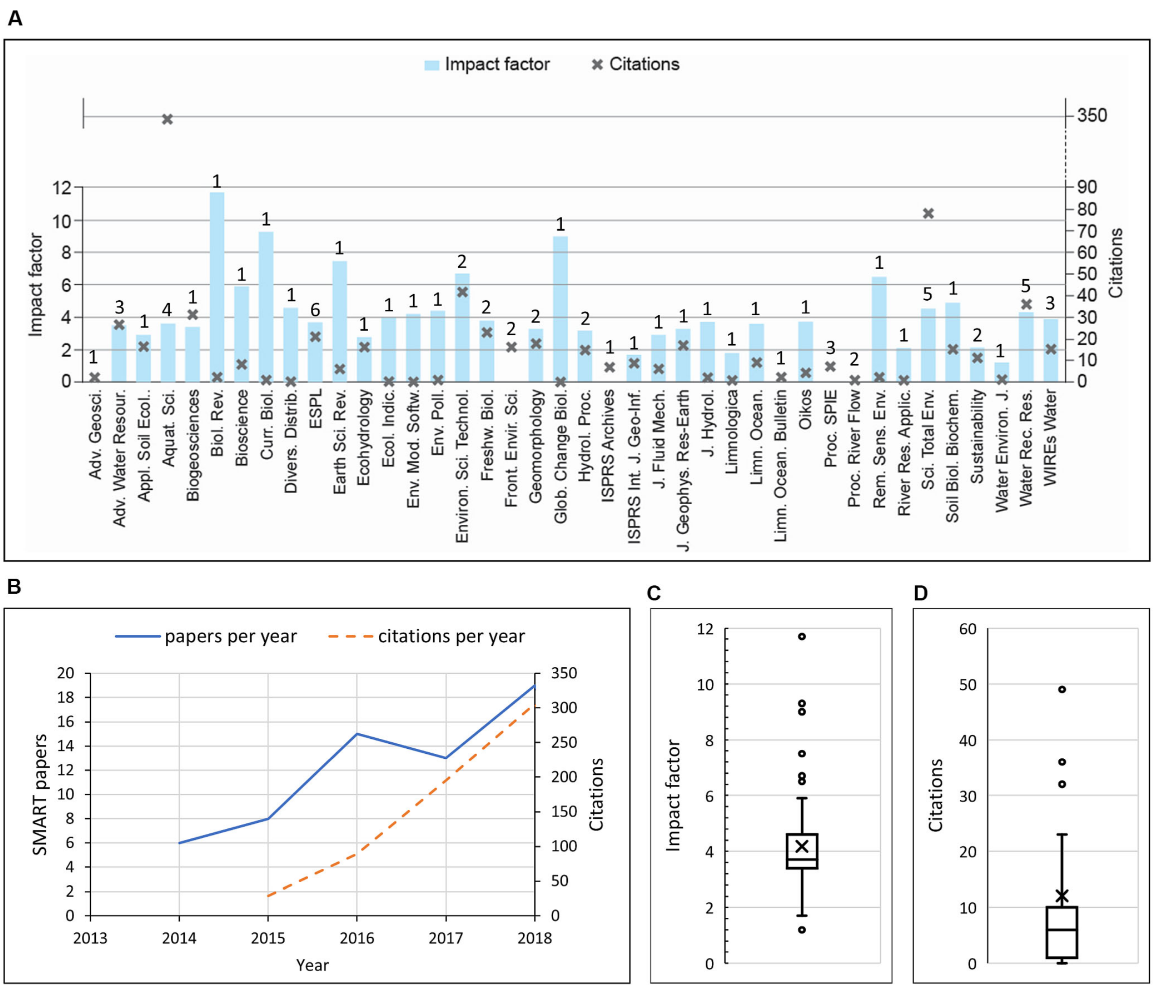


FIGURE 3 | (A) Impact factor and citations per journal or conference proceedings with numbers above bars indicating the total number of published papers within the corresponding journal; **(B)** papers published in the SMART EMJD and related citations per year; boxplots showing distributions of **(C)** journal impact factor and of **(D)** the number of citations for all papers. The horizontal line within the box represents the median, the mean is presented with a cross symbol, outliers as circles, the quartiles are calculated excluding the median (papers and number of citations considered up to March 2019).

Among the supervisors, 69% of the survey participants agreed/fully agreed that their knowledge improved in disciplines beyond their original areas of expertise and 65% of the supervisors indicated that the program has led them to explore other research areas. 50% also stated that the interdisciplinary nature of the Ph.D. topics led to higher quality science compared to topics from traditional disciplinary areas.

Doctoral Theses and Publications

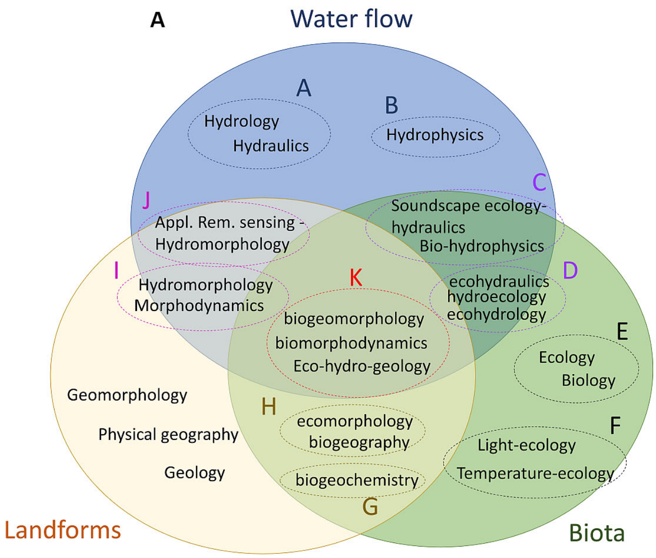
Figure 4A illustrates the identified research foci across all doctoral theses within the three major components: water flow, landforms, and biota. **Figure 4B** lists the percentage contribution of these research foci to the ensemble of the 36 doctoral theses. Interdisciplinary research between the three research components predominates, with 81% of the investigated work concentrated in two or more research foci. Nearly 1/3 of the theses covered the three major components (subgroup K) while only 19% covered one.

Figure 5A presents the total number and relative proportion of papers (from a total of 66 Scopus-indexed SMART EMJD papers) addressing the subject areas associated with the journals within the Scopus databases. **Figure 5B** displays the subject areas for the 709 papers citing the SMART EMJD papers. The results show a similar distribution of the subject areas across published papers and citing papers with environmental science (32 and 36%), agricultural and biological sciences (18 and 23%), earth and planetary sciences (15 and 14%) jointly cover nearly 70% of all identified disciplines.

Disciplinary Backgrounds

Table 1 shows the backgrounds of the doctoral candidates and supervisors for each of the SMART EMJD partner institutions.

From 34 supervisors, 18 had a background within either the ECO, GEO or HYDRO research components, one within geomatics, and 15 already exhibited an interdisciplinary expertise. Each doctoral candidate was appointed to at least two



B

		%
A	Hydrology/Hydraulics	2
B	Hydrothermodynamics Physical hydrology	7
C	Soundscape ecology - hydraulics Bio-hydro-physics	4
D	Ecohydraulics Ecohydrology Aquatic ecology	13
E	Ecology/Biology	2
F	Light-ecology Temperature-ecology	8
G	Biogeochemistry	5
H	Ecomorphology Biogeography	8
I	Hydromorphology Morphodynamics	15
J	Applied remote sensing - hydromorphology	6
K	Biomorphodynamics Eco-hydro-geology	29

FIGURE 4 | (A) Overview of research foci in the SMART EMJD, within the three major river science components: Water flow, Biota and Landforms. **(B)** Percentage contribution of each research focus across all the 36 doctoral theses.

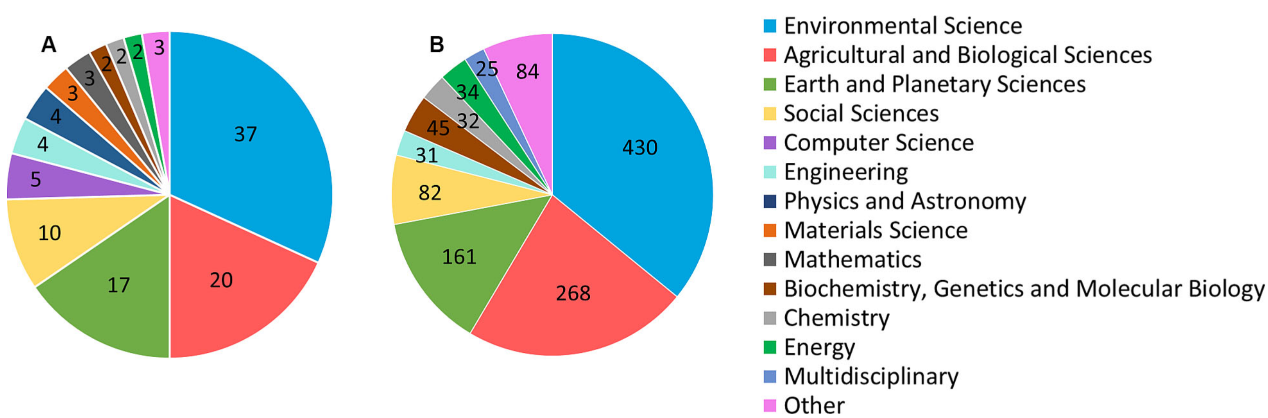


FIGURE 5 | The proportion of different subject areas (size of pie slices) and related number of Scopus documents associated with the journals in which **(A)** the 66 Scopus-indexed SMART EMJD papers have been published and **(B)** all 709 papers citing the SMART EMJD papers have been published.

TABLE 1 | Initial backgrounds of the SMART EMJD doctoral candidates and supervisors per institute.

		ECO	HYDRO	GEO	GEO-MATICS	ECO-HYDRO	GEO-HYDRO	ECO-GEO	ECO-HYDRO-GEO	BIO-GEO-CHEM.	Total
University of Trento	Supervisors		3		1		4				8
	Candidates	2	10		1	2					15
Queen Mary University of London	Supervisors			1			1	1	2	2	7
	Candidates	2	2			3	1				8
Freie Universität Berlin	Supervisors	6	2			3				1	12
	Candidates	10	1					2			13
Associate partners	Supervisors	4	2				1				15

and up to four supervisors. During the SMART EMJD, there were 110 connections established among the 34 supervisors and 36 doctoral candidates. For 35% of those connections, the candidate had a different disciplinary background to the supervisor while for 65% of connections the topical focus was similar. **Figure 6** indicates the growth of the network among supervisors by comparing the existing network before the SMART EMJD (**Figure 6A**) and at the end of the program (**Figure 6B**). A total

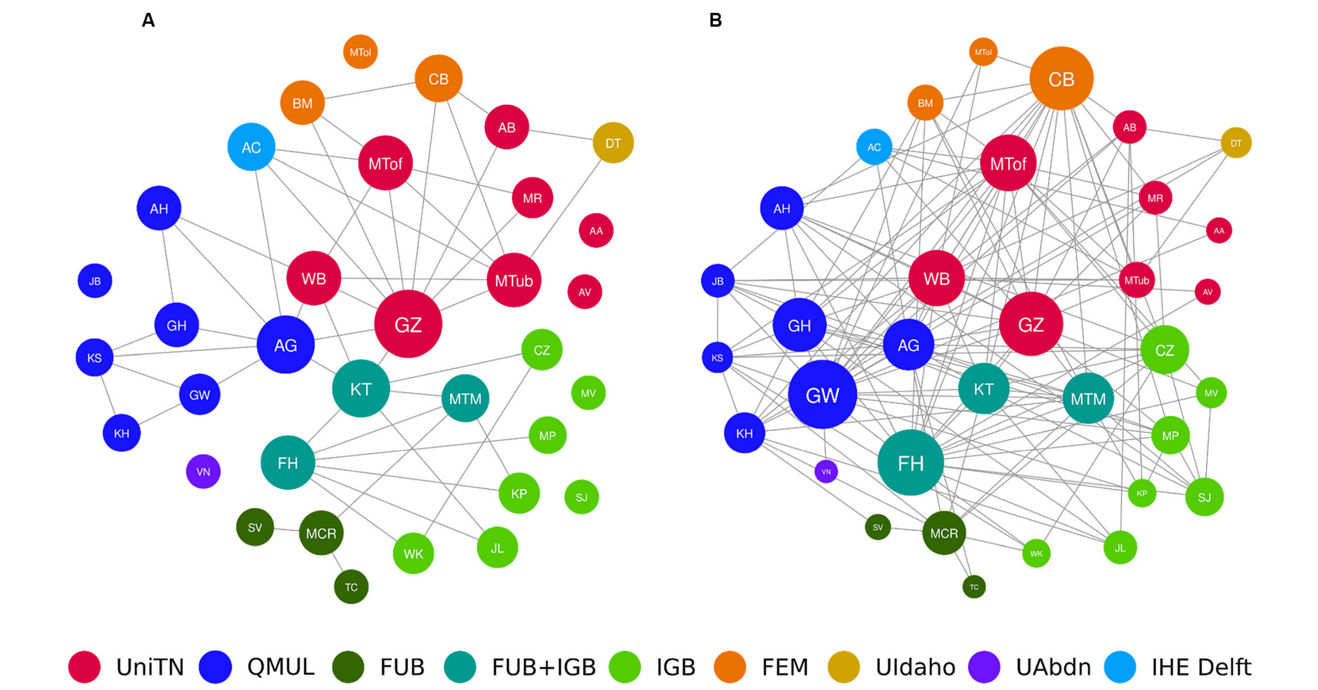


FIGURE 6 | Network maps presenting the scientific connections between supervisors: **(A)** before the start of the SMART EMJD, and **(B)** after the SMART EMJD. Node size is proportional to the relative amount of connections of the supervisor.

of 86 new connections were established corresponding to an increase of 183%.

The interdisciplinary research foci assigned to the doctoral theses (**Figure 4A**) were further compared to the backgrounds of the SMART EMJD doctoral candidates and supervisors. On average, doctoral candidates and supervisors were introduced, respectively, to 1.4 and 1.8 new research foci.

Internationalism

The international dimension of the SMART EMJD was founded upon the recruitment of candidates from EU and non-EU countries working with supervisors from different nationalities, upon the mobility requirements of the program, and upon the locations of the training weeks, meetings and field sites.

The international collaboration within the SMART EMJD primarily occurred within each individual doctoral research project, in which candidates and supervisors were often from different nationalities. Internationalism was further enhanced through periodical meetings and workshops, including an "Annual Week" during which the progress of each doctoral candidate was presented to all participants and assessed by the Academic Board of the program. The Annual Week provided an effective forum for high quality, regular scientific interactions among the doctoral candidates and the supervisors. The doctoral program further allowed doctoral candidates to spend time at different institutes and associate partners providing access to international field sites.

All doctoral candidates who participated in the survey agreed that working in an international context improved their research. Most candidates (96%) agreed that it further improved their capability and preparedness to work in an international environment. In addition, a very strong (global) community was built between the SMART EMJD doctoral candidates and supervisors, which may last for many years, facilitating future opportunities in science and beyond.

SMART Applicants and Doctoral Candidates

In total, 378 eligible candidates applied for the SMART EMJD program (all five cohorts). **Table 2** provides an overview (per cohort) in comparison with all Erasmus Mundus Joint Doctorates for 2015. For the SMART EMJD, the total number of applicants increased after the first year, suggesting a growth in awareness and international recognition of the program. In the 4th and 5th call, applicants were asked where they learnt about the program, with 46 and 53%, respectively, reporting the official SMART EMJD website[2] as the main source. The second source was oral communication (21 and 15%, respectively), while all others indicated other sources of information.

The largest number of applications came from Asia, followed by Europe, Africa and America with no applications from Australia and Oceania. A similar trend was observed in the number of applicants to all EMJDs, although the SMART EMJD had a lower proportion of African and a higher proportion of European applicants.

The proportion of selected doctoral candidates was highest for Europe, followed by Asia, North and South America and Africa. Compared to SMART, all EMJDs supported by

[2]www.riverscience.it

TABLE 2 | Number of applicants (top panel, *n* = 378) and doctoral candidates (bottom panel; *n* = 36) per year and continent for the SMART EMJD and total applicants and doctoral candidates in all EMJDs (including SMART) in 2015.

	SMART EMJD program						All EMJD programs	
	Applicants					% total	Applicants	% total
	2011	2012	2013	2014	2015		2015	
Africa	11	17	12	16	20	**20**	824	**27**
Asia	23	29	36	29	44	**43**	1373	**45**
Australia and Oceania	0	0	0	0	0	**0**	11	**0.4**
Europe	17	25	20	19	24	**28**	621	**21**
North-America	2	5	5	5	1	**5**	99	**3**
South-America	2	3	3	3	7	**5**	100	**3**
Total	**55**	**79**	**76**	**72**	**96**		**3028**	
	Doctoral candidates					**% total**	**Candidates**	**% total**
	2011	**2012**	**2013**	**2014**	**2015**		**2015**	
Africa	0	1	0	0	0	**3**	12	**10**
Asia	4	2	3	3	1	**36**	57	**47**
Australia and Oceania	0	0	0	0	0	**0**	1	**1**
Europe	4	4	3	3	2	**44**	29	**24**
North-America	2	0	0	1	0	**8**	13	**11**
South-America	0	0	1	0	2	**8**	10	**8**
Total	**10**	**7**	**7**	**7**	**5**		**122**	
% selected	18	9	9	10	5		4	

EACEA had slightly more doctoral candidates from Asia and Africa and less from Europe. The number of selected European doctoral candidates, however, is also influenced by the number of designated Erasmus Mundus scholarships for EU citizens. The selection rate is presented in the final row of **Table 2**, indicating the number of selected doctoral candidates over the total applicants. The selection rate varied among SMART EMJD cohorts and was higher than the average figure reported for all EMJDs.

Figure 7 presents an overview of the movement of the doctoral candidates from their home countries to their destination countries at the beginning and end of the SMART EMJD, respectively. Of the 15 EU and 21 non-EU doctoral candidates, 26 now reside in the EU while 10 reside outside the EU. 14 doctoral candidates remained in the country of their primary institution (for 5 their country of origin), 10 returned to their home country, and 10 moved to another country.

International Collaboration and Research

Besides online communication and interactions within each institution, the Consortium-wide meetings included the SMART Annual Week and yearly meetings to select new doctoral candidates and to assess the admission of 3rd-year candidates to the final defense. These meetings fostered international collaboration and development of professional networks both for the doctoral candidates and the supervisors. The research presentations and discussions and social events (field trips, informal lunch gatherings and dinners) were also a key element in breaking down disciplinary boundaries by creating multiple opportunities to communicate with one another and address differences in approaches and terminology. The location of the Annual Weeks started on the braided Tagliamento River in NE Italy, where previous collaboration among the lead scientists of the program started, and then rotated on a 3-year cycle between Trento, Berlin and London including local fieldtrips. The Annual Training Weeks were attended by all enrolled doctoral candidates and by nearly all supervisors. Total duration of these meetings covered 48 days over 8 years and participation can be quantified as a total of 1184 person-days when summing the actual presence of each individual (**Figure 8**). International collaboration was further promoted through the compulsory 6-month mobility to a secondary institution, which is quantified in **Figure 8**.

Candidate mobility between different institutes and associate partners also provided opportunities to access international field sites and the fieldwork itself facilitated further international collaboration. Fieldwork was a component of 24 out of the 36 research projects with the majority of candidates working outside their home country. Fieldwork was undertaken by 10 doctoral candidates in Italy (e.g., Cashman et al., 2017; Zen et al., 2017; Brighenti et al., 2019), 7 in Germany (e.g., Grubisic et al., 2018; Gaona et al., 2019), 6 in the UK (e.g., Faller et al., 2016), 3 in Poland (e.g., Pilotto et al., 2014), 1 in the Netherlands (Belliard et al., 2016), 1 in France (Serlet et al., 2018), and 1 in Romania. Four doctoral candidates did fieldwork in more than one European country. Six SMART EMJD doctoral candidates further analyzed data from one or more rivers using existing national or international databases and GIS analysis in Europe. Three doctoral candidates studied and used existing data of rivers or other freshwater systems in Africa and South America (Monegaglia et al., 2018), New Zealand (Redolfi et al., 2016),

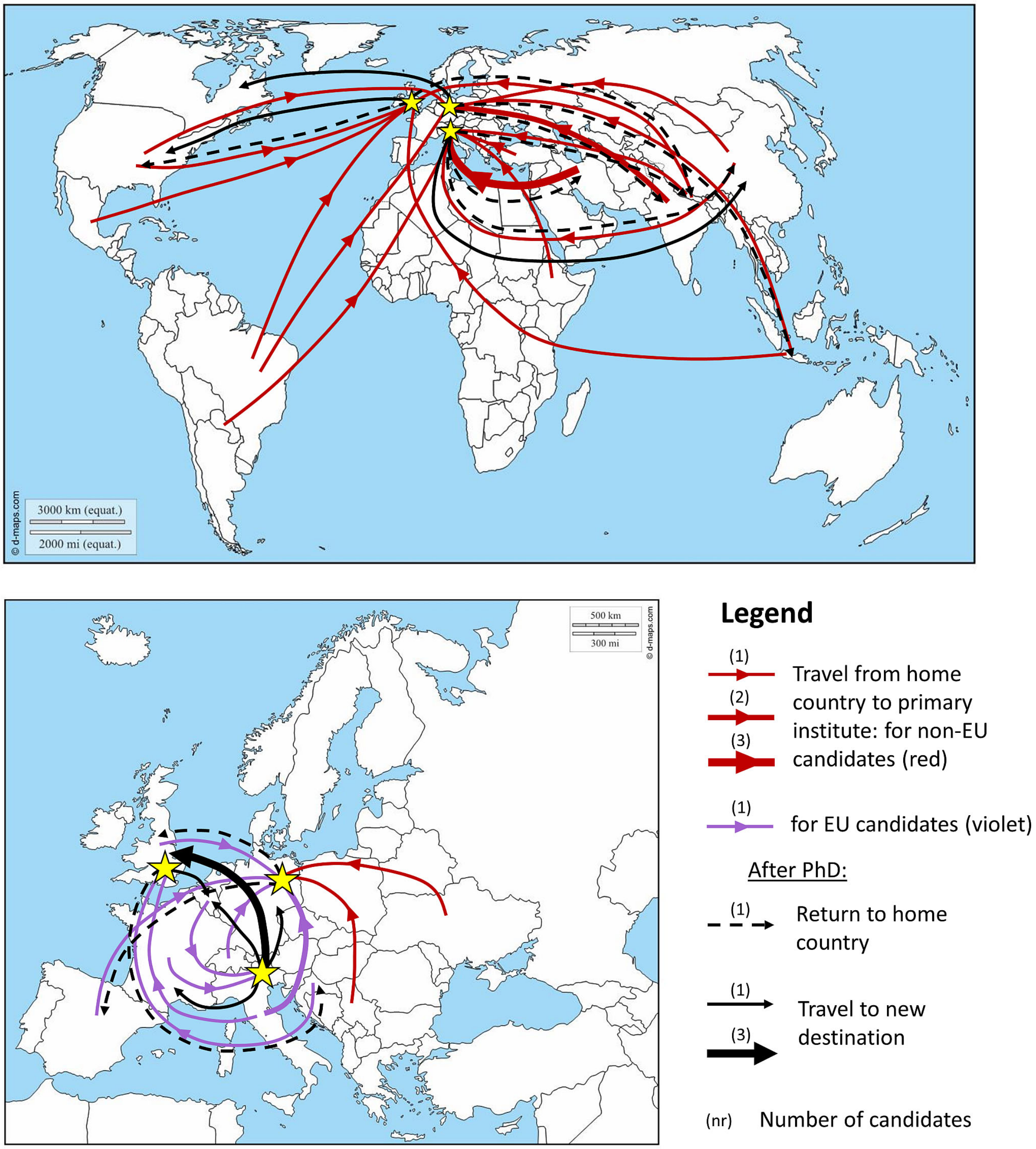


FIGURE 7 | Arrows indicate the movement of doctoral candidates from their home countries to the primary institutions at the start of the program (in red) and for those who did not stay in the same country their return to either their home country (black intermittent arrow) or to a new destination (black arrow). The upper panel shows a global map with travel between Europe and other continents, the lower panel presents a map of Europe with travel within Europe.

and Paraguay (López Moreira M et al., 2018). Finally, 4 doctoral candidates compiled existing data sets for global-scale studies (e.g., He et al., 2019; Shumilova et al., 2019).

Management – Oriented Science

A first assessment of management-oriented science within the SMART EMJD was derived from an analysis of the alignment of each thesis with the three research areas (a, b, and c, see **Figure 2** and description of the case study under Methods). The most prevalent research area was (b) natural functioning (57%), followed by (a) ecosystem resilience to stressors (34%), and finally, (c) rehabilitation of functions (9%), which was the area most directly linked to river management. Research projects in area (c) included: river restoration using large wood and/or vegetation, hydropower management related to sediment flushing, hydro-peaking, and vegetation encroachment,

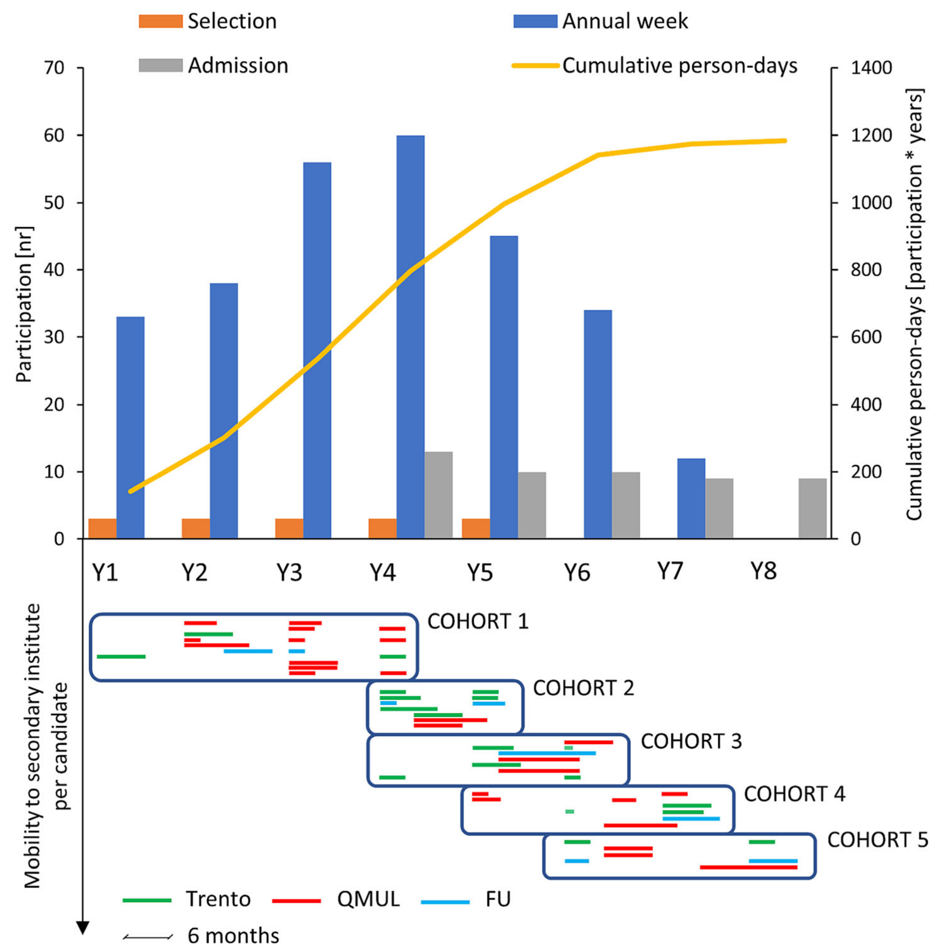


FIGURE 8 | On top: Participation for each meeting event (selection, annual week, and admission) and cumulative days of these meetings. Below: Overview of secondary mobility over time of all doctoral candidates with color indicating the institute.

conservation management and rehabilitation of contaminated (from e.g., heavy metals, nutrients) rivers and lakes. Other indirect links with management included habitat assessment and mapping, reconstructing trajectories in understanding the natural reference conditions, studies on impacts such as artificial light, invasive species, and hydropower.

Collaboration with river managers was more limited than anticipated (see Discussion). Only 12% of the doctoral candidates who participated in the survey confirmed collaborations with organizations directly involved in river management and only three doctoral candidates had an Associate Partner (Environment Agency, United Kingdom) who was directly involved in river management although some doctoral candidates working on impacted rivers and lakes had productive local collaborations for sharing data and knowledge.

In terms of career profiles, at the time of this study, 18 alumni started/continued working in academia, 6 in governmental institutions, 4 in the private sector, 4 in research institutions or an NGO and 1 was unemployed. From the survey, 60% of the doctoral candidate participants and 54% of supervisors believed that the SMART EMJD improved their employability in the river management sector. Overall, 22% of the jobs secured were directly related to management (13% associated with human impacts and 9% linked to policymaking, planning and regulatory services). The remaining 78% of SMART EMJD alumni were involved in other dimensions of river or environmental science not directly related to management.

DISCUSSION

Interdisciplinary approaches and collaboration are necessary to address the most pressing socio-ecological challenges humankind is facing[3], including securing one of our most valuable resources: freshwater ecosystems (Bunn, 2016). Doctoral training programs that move beyond “disciplinary silos” and cut across traditional boundaries provide “fertile environments for collaborative research” (Borrego and Newswander, 2010) and are fundamental to building interdisciplinary research capacity globally. More

[3]http://www.millennium-project.org/projects/challenges

knowledge is needed on the practical and intellectual processes involved in interdisciplinary research training and what Gardner (2013) has called the "socialization to interdisciplinarity." Our reflections on the 9-year SMART EMJD doctoral training program and the lessons learned from an analysis of the three core facets of the program – (1) interdisciplinarity; (2) internationalism; and (3) management-oriented science – help allay some concerns about interdisciplinary training and provide insights for future river science training.

Scientific Outputs and Impacts

The most obvious scientific outputs and impacts of the program are the publications and more are anticipated from manuscripts currently in preparation or under revision. Millar (2013) found that graduates of interdisciplinary research programs tend to achieve a higher publications record. However, the average number of first authored publications before the defense was lower for SMART candidates compared to those in established institutional Ph.D. programs at the three universities. It has to be acknowledged that most SMART candidates had to adapt to a different cultural setting, were required to finish in about 3 years, and had to spend extensive time at two institutions in different countries. At the same time, a higher proportion of first-authored papers for SMART candidates indicates a higher degree of independence and a stronger focus on the specific research goals. Overall, the comparison suggests satisfactory rates of scientific publishing were achieved for the SMART program.

The research outputs covered a very broad spectrum of research foci reflecting how doctoral candidates were exposed to a broad array of research areas. Indeed, it is an ambition of the program to establish longer-term international and interdisciplinary networks and wider career options, to address novel questions and distinct recommendations for river science and management, as well as to meet a broad audience (e.g., Mardhiah et al., 2014; Zarfl et al., 2015; Bodmer et al., 2016; de Souza et al., 2016; Faller et al., 2016; Redolfi et al., 2016; Manfrin et al., 2017; Serlet et al., 2018). Furthermore, as the publications are very recent, citations are expected to increase.

The added value of working in an international and interdisciplinary context resulted in knowledge and appreciation of different perspectives to be gained from other disciplines. The doctoral training program supported the formation of new collaborative research teams, which both doctoral candidates and supervisors found rewarding in terms of gaining skills and insights into disciplines, methods, and organizational structures beyond what a "classical" doctoral project may offer. Established researchers expanded their international and interdisciplinary collaborations through the doctoral supervision and there is a strong motivation from former supervisors and alumni from the program to maintain and grow the networks.

Employability from the program was high and provides reassurances to counter the frequently voiced concern that interdisciplinary researchers face enhanced barriers to career success as has often been the concern (e.g., Loeb, 2020). Programs like SMART EMJD which aim to provide science for management by balancing international experience with established locally-centered practices (Pinter et al., 2019) are perhaps helping to encourage graduates to pursue careers in environmental management as well as science opening up new career opportunities.

Challenges

Despite the many achievements of the SMART program, there remained challenging aspects. Collaboration among different groups and the integration across research projects was limited and the opportunities offered by the program were not fully exploited and, therefore, may have confined additional insights and publications. However, this was difficult to achieve within the constraints of 3 years of doctoral training, including mobility requirements. These constraints may have also limited the average number of publications before the defense and may in some cases represent a disadvantage for candidates when searching for future employment in academia.

The SMART program aimed to attract the strongest applicants globally. However, attracting students from North America and especially Australia and Oceania was a challenge and the reasons are unclear. This trend was mirrored across all EMJDs, so additional efforts will be needed to integrate these continents in future EU-funded programs.

The international aspects of the program, including the mandatory mobility, presented practical challenges compared to other doctoral programs. Key difficulties included finding short-term housing in the different research locations, getting acquainted with new administrative regulations, building up new professional and social relationships, assembling field equipment at new institutions and using new laboratory facilities. Asking for and receiving proper support was easy for some but very challenging for others especially when exacerbated by language barriers that could be mentally straining.

While having an international supervisory team was for most candidates an enriching experience, a few doctoral candidates reported conflicting needs including different goals in research, different styles of writing, as well as diverging expectations. Ensuring regular contact among the team members (for example through frequent Skype meetings) is critical to keep everyone "on board," and designated local support contacts can help to advise on differing institutional requirements such as research progress reporting and thesis structure.

The SMART EMJD was established with a clear goal to integrate river science and management. However, only 9% of all research outputs from the doctoral theses are directly related to the rehabilitation of impacted river systems. Practical barriers to securing placements with environmental management organizations and companies sometimes meant that direct collaboration with river managers and close integration of science and management was more difficult to achieve than anticipated. But a more widespread problem identified in the survey was the ambitious combination of interdisciplinary, international, and management-oriented approaches within in a 3-year doctoral program. The completion of the scientific components including the doctoral thesis, research papers, and presentations at international science conferences were necessarily prioritized. And doctoral candidates undertaking extended periods of intense fieldwork and/or laboratory work struggled to allow sufficient time to develop recommendations for managers.

Finally, awarding a joint doctoral degree between universities belonging to different countries, even within the context of the EU, raised many administrative challenges and required a spirit of compromise. New institutional agreements were put in place that followed the doctoral regulations in place at the primary institution of each candidate and set minimum requirements that could also be accepted by the secondary institution.

CONCLUSION

We have assessed the contribution of a 9-year European doctoral program in river science ("SMART" Erasmus Mundus Joint Doctorate), led by three universities with complementary expertise (engineering; ecology; geomorphology). The program trained 36 doctoral candidates under the supervision of 34 senior researchers with an interdisciplinary and international focus on river systems, aiming to move across the boundaries between science and management. The program was analyzed by reviewing contents of doctoral theses and peer-reviewed, international indexed publications, as well as by synthesizing the outcomes of two assessment questionnaires directed to doctoral candidates and supervisors.

Results focused on the three core facets of the SMART EMJD: (1) interdisciplinarity; (2) internationalism; and (3) management-oriented science. We found that the doctoral program resulted in a highly interdisciplinary (80% of publications) and consistent scientific output, consisting of 69 published papers (of which 66 were Scopus-indexed) papers at the time of performing the analysis for this paper. Through an approximate comparison with the number of indexed papers resulting from "standard," institutional doctorates focused on rivers in the same institutions, it emerges that SMART candidates produced fewer papers on average before their defense, however, a larger proportion was first-authored. Despite the challenges posed by such an ambitious program completion rates and employment were good. In total, 86% of all SMART EMJD candidates successfully completed the doctoral program and nearly all (97%) doctoral candidates were employed very soon after being awarded a joint doctoral degree in river science by two of the partner institutions of the SMART program. Employment occurred both in river-related research (50%) and private/public sector (50%) and was strongly international, likely reflecting the international dimension of the program.

As such, the success of this program is reflected mainly in the large number of peer-reviewed articles with a high degree of interdisciplinarity, a high mobility of the doctoral scientists among the international partners, and a successful career progression, mainly in river science, after award of the doctoral thesis. The three main features that facilitated this success are: (1) the combination of supervisors from different disciplines and their inherent motivation to work across and beyond their own expertise and provide science for river management; (2) the sound (inter)disciplinary background, motivation, and openness of the selected doctoral candidates in taking up the challenge; and (3) the mobility schemes that were integrated in the schedule of each doctoral candidate's study program.

Such an interdisciplinary and international program required a huge commitment by the partner institutions including doctoral candidates, supervisors, and administrative staff with nearly 1200 person-days of joint assessment and scientific meetings in addition to the compulsory mobility arrangements for individual doctoral candidates. But we witnessed the importance of these scientific and social gatherings in enabling interaction and providing the environment in which creativity, novel ideas and solutions, and new opportunities could emerge. We are optimistic that the strong interdisciplinary and international networks fostered within SMART will provide a platform for future research collaborations.

Going forward we hope that future doctoral training programs in river science can learn from programs like SMART and other successful programs closely connected to river management such as the IGERT Ph.D. program in the United States[4], recognizing and working to overcome some of the key challenges (Lindvig and Hillersdal, 2019). Funds to allow graduate mobility and research across multiple river systems are critical and we might also work to realize Geoff Petts' aspiration for a "global river science graduate school" with research students connected by regular e-seminars (Petts, 2013). Integrating new methods and disciplines, including those related to social and human sciences, will also be an important step forward to advancing understanding and management of "rivers as socio-ecological systems" (Kingsford et al., 2011).

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

AS was responsible for manuscript coordination and contributed to the preparation of surveys, data processing, analysis, and preparation of results and writing. GL contributed to the preparation of surveys, data processing, analysis, and preparation of results and writing. GZ and GW contributed to conception and design of the study and extensive revisions and writing. FH, AG, KT, WB, MB, SJ, JL, MM, MCR, MT, SV, and CZ contributed with revisions, comments, and minor writing. MR contributed to the preparation of the first surveys, data collection and processing, and preparation of administrative reports. All authors read and approved the final version of the manuscript.

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[4] http://igert.siu.edu/

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2020.00063/full#supplementary-material

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