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Gaining insight into interdisciplinary research and education programmes: A framework for evaluation

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ABSTRACT

Greater understanding of how interdisciplinary research and education evolves is critical for identifying and implementing appropriate programme management strategies. In this paper a programme evaluation framework is presented. It is based on social learning processes (individual learning, interdisciplinary research practices, and interaction between researchers with different backgrounds); social capital outcomes (ability to interact, interpersonal connectivity, and shared understanding); and knowledge and human capital outcomes (new knowledge that integrates multiple research fields). The framework is illustrated on an established case study doctoral programme. Data are collected via mixed qualitative/quantitative methods to reveal several interesting findings about how interdisciplinary research evolves and can be supported. Firstly, different aspects of individual learning seem to contribute to a researcher's ability to interact with researchers from other research fields and work collaboratively. These include learning new material from different research fields, learning how to learn new material and learning how to integrate different material. Secondly, shared interdisciplinary research practices can be identified that may be common to other programmes and support interaction and shared understanding between different researchers. They include clarification and questioning, harnessing differences and setting defensible research boundaries. Thirdly, intensive interaction between researchers from different backgrounds support connectivity between the researchers, further enabling collaborative work. The case study data suggest that social learning processes and social capital outcomes precede new interdisciplinary research findings and are therefore a critical aspect to consider in interdisciplinary programme management.

1. Introduction

Real world problems rarely regard disciplinary boundaries. Research that reflects the integrated nature of societal problems by joining together knowledge and understanding from different disciplines is essential to address the challenges facing society (Carayol and Nguyen Thi, 2005; Jeffrey, 2003; Klein, 1990; Repko, 2008). This is particularly apparent regarding water, essential for life and our economy and therefore an integral part of every aspect of our lives. A holistic approach to understanding water systems in their entirety is critical for sustainable management and requires research that takes place across multiple disciplines (Daily and Erhlich, 1999). Interdisciplinary research and education programmes aim to address this need by producing new knowledge through research collaborations across different research fields, while at the same time, developing interdisciplinary research skills in the future generation of researchers (Blöschl et al., 2012). Yet several authors have noted that greater efforts are needed in evaluating the effectiveness of such programmes in order to both demonstrate their value and understand how they can be improved (Boix-Mansilla and Dawes Duraising, 2007; Borrego and Cutler, 2010; Mitrany and Stokols, 2005; Saito et al., 2013).

Defining interdisciplinarity and determining its objectives is complex (Barry and Born, 2013; Klein, 2006; Siedlok and Hibbert, 2014). A broad and commonly used definition of interdisciplinary work is provided by the OECD, “interaction between two or more different disciplines. The interaction may range from simple communication of ideas to the mutual integration of organising concepts, methodology, procedures, epistemology, terminology, data and organisation of research and education in a fairly large field” (OECD, 1972 p. 25). This is somewhat different to the definitions of multi-disciplinary work, “the juxtaposition of various disciplines, sometimes with no apparent similarity between them," and transdisciplinary work, ‘establishing a common set of axioms for a set of disciplines’ (OECD, 1972 p. 25). Over the last few decades these definitions have been extensively revised and

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adapted (see Huutoniemi et al., 2010 for a comprehensive overview) and the range of conceptualisations are diverse. Some aim to capture the nature of the interactions (e.g. symmetrical or asymmetrical integration of two or more disciplines (Barry and Born, 2013)), others are concerned with the products that result (e.g. knowledge or methods (Schmid 2008, 2011)), and some include the participants involved and the expected beneficiaries of the resulting research (e.g. engagement beyond academics and academia (Pohl, 2011)). Two common themes tend to emerge. One is that the discipline is not the central construct for the research, rather the research question determines the disciplines that engage in the research, also known as mode-2 knowledge production (Gibbons et al., 1994; Nowotny et al., 2001) Another is that multi-, inter- and trans-disciplinary are often thought of as points on a continuum, rather than being mutually exclusive typologies (Golde and Gallagher, 1999; Huutoniemi et al., 2010). In this paper we have chosen to use the term cross-disciplinary to capture multi-, inter- and trans-disciplinary type research. We later differentiate between multi- and interdisciplinary work using the framework developed by Huutoniemi et al. (2010). We specifically explore research taking place between researchers from different research fields rather than also including cross-disciplinary work conducted solely by an individual or work that includes non-academic stakeholders (Pfirman and Martin, 2010).

Researchers have attempted to measure interdisciplinary outcomes in ways such as: i) the diversity of the journals in which a researcher has published (Carayol and Nguyen Thi, 2005); ii) the successful integration of knowledge and understanding through the forging of new fields or disciplines (Borrego and Newswander, 2008; Corley et al., 2006; Golde and Gallagher, 1999); or iii) the production of new knowledge, and the quality and quantity of that knowledge as measured by publications, grants, awards and citations (Carr et al., 2017; Porter et al., 2006; van Rijnsoever and Hessels, 2011; Wagner et al., 2011). Klein (2006, 2008) notes how objectives from interdisciplinary projects vary. New knowledge is one type of goal, but others may be the development of new approaches or products (e.g. medicines or measuring devices). The findings of these studies generally reveal that interdisciplinary programmes are leading to a variety of outcomes. However, we do not know enough about how these outcomes are emerging, what the factors are that support their development and ultimately, how we can increase the quality and quantity of interdisciplinary research. A framework is needed that can capture the outcomes, and couple them to the processes taking place within a programme that are leading to their achievement.

This paper aims to address this research need by proposing and illustrating the application of an interdisciplinary evaluation framework. We present a conceptualization of the interdisciplinary system for the interdisciplinary research community that captures processes and tangible and intangible research outcomes. Using the framework, we explore why and how interdisciplinary research is taking place in a case study doctoral programme. This leads to some observations about the linkages between processes and outcomes in interdisciplinary research programmes, and some general recommendations on how interdisciplinary research can be supported that may be of benefit to those engaged in such programmes. First a brief overview of the case study is given then the framework is explained. The indicators and data sets used to operationalize the case study evaluation are described and the results are presented. Some general recommendations for interdisciplinary programmes are drawn, and the framework is critically reviewed and the areas for further development are identified.

2. The case study: Vienna Doctoral Programme on Water Resource Systems

The Vienna Doctoral Programme on Water Resource Systems (www.waterresources.at) at Vienna University of Technology began in 2009 with funding from the Austrian Science Fund (FWF) and from the university. It is currently in its eighth year and is designed to run over a period of 12 years. An anticipated 70 students will have graduated by 2021. The goal of the programme is to achieve interdisciplinary cutting edge research at the international level and turn out graduates who go on to work in leading organisations from the public, private and academic sectors. To this aim, students complete their PhD through publications in international peer reviewed journals (a minimum of three papers where the student is first author are required). Researchers are encouraged to submit their work to one of the leading journals in their field (based on journal impact factor).

Ten research fields are included in the programme reflecting the university departments and research focus of each of the ten faculty members – aquatic microbiology, hydrology, hydro-climatology, hydro-geology, mathematical economics, photogrammetry, remote sensing, resource management, structural mechanics, and water quality. These are described as *research fields*, as they represent groups of researchers addressing knowledge domains, rather than traditional academic disciplines (Huutoniemi et al., 2010). Since the start of the programme, 50 international doctoral students with diverse academic backgrounds have been enrolled and to date, 24 have graduated. Seven programme graduates continue to be involved as associate post-docs, along with three other associate post-docs (one of whom is the programme coordinator). Efforts have been made from the onset of the programme to create a physical and intellectual environment conducive for interaction among the researchers through implementing a number of approaches, described in Table 1.

Table 1
Approaches to promote cross-disciplinary interaction in the programme.

Approach	Details
Shared offices	One open plan office hosting 7 students and programme coordinator. Other students hosted in their supervisors' departments, 8 of which plus programme office are located in the same building, Two are located in different buildings.
Study programme	Each faculty member teaches a compulsory basic course on their research field which each student must take, and students can chose from a variety of elective courses for more advanced study on topics that interest them.
Seminar series	A monthly seminar series given by leading researchers from around the world on topics of interest to programme researchers.
Research cluster meetings	Each programme participant is a member of at least one research cluster group (water resource management, land-surface processes, Hydrological Open Air Laboratory, water and health, modelling and risk). The regularity of their meetings (monthly to six-monthly) and content (presentations by members of the group, review of manuscripts, or research planning such as fieldwork and experiments) varies considerably between the clusters.
Joint supervision	Each student has a primary supervisor and a supporting supervisor from different research fields.
Annual and six-monthly symposia	Symposia bring all members of the programme together for one day (six-month symposium) or two days (including an overnight stay away from the university) (annual symposium). They typically involve short presentations and posters from research students on their research progress, extended questioning time to stimulate discussion, workshops and small group meetings for brainstorming, and evening group games to promote informal interaction between all programme researchers.
Shared study sites	In the shared field study sites students with different specialisations work directly together to address their research questions. For example, in the Hydrological Open Air Laboratory (HOAL) and the Danube Porous Aquifer (both located close to Vienna) students support each other in data collection and designing and conducting experiments (see Blöschl et al., 2015 for details of the HOAL).

Table 2
Empirical findings from the literature on interdisciplinary collaboration grouped according to processes, intermediary outcomes and research and education outcomes.

Evaluation criteria	Empirical findings supporting the criteria	Indicators and data sets used
Processes		
Individual learning		
Learning about new research fields	Sufficient understanding of other research topics enables researchers to communicate with one another and respect each other's epistemological standpoints (Borrego and Newswander, 2008).	Interviews with engineer-non engineer research teams to explore important factors for cross-disciplinary collaboration (Borrego and Newswander, 2008).
Learning the differences between, and limitations of, the disciplines	Acknowledging and analysing the differences between the disciplines is part of the learning process in interdisciplinary research (Haapasaari et al., 2012).	Case study analysis using ethnographic methods to identify factors important for interdisciplinary research (Haapasaari et al., 2012).
	Researchers need to learn to recognise the limitations to their own knowledge and/or disciplinary based approach/methodology in order to seek out supporting expertise and/or alternative understandings to address their research question (Hibbert et al., 2016).	Case study analysis using ethnographic methods (Hibbert et al., 2016).
Identifying collaborators	Researchers need to learn to identify the characteristics needed in potential collaborators (e.g. their expertise, intellectual openness, personal disposition) and secure their support (Boix-Mansilla et al., 2012; Siedlok et al., 2015).	Interview data from researchers from nine research networks (Boix-Mansilla et al., 2012).
		Observations of an interdisciplinary initiative and interviews with interdisciplinary researchers to identify features of interdisciplinary research practice (Siedlok et al., 2015).
Learning to communicate	Researchers need to learn how to communicate their research in a way that makes their knowledge accessible to those from other research fields (Jeffrey 2003; Olsen, 2009; Siedlok et al., 2015).	Case study analysis using ethnographic methods to identify factors important for interdisciplinary research (Haapasaari et al., 2012; Jeffrey, 2003; Olsen, 2009).
Developing shared interdisciplinary research practices		
Clarification	Discussing and re-explaining one's research (exposing all the assumptions being made) until all involved in the discussion understand it and have a "shared interpretive horizon" (Jeffrey, 2003; Hibbert et al., 2016; Siedlok et al., 2015).	Case study analysis using ethnographic methods to identify factors important for interdisciplinary research (Jeffrey, 2003; Hibbert et al., 2016).
Harnessing differences	Managing potential sources of conflict due to the different ideas, interests and personalities being brought together, not with the aim of eliminating them (because they stimulate creativity), but to minimise the tensions and disputes which prevent people from working together constructively (Bammer, 2008; Boix-Mansilla et al., 2012; Borrego and Newswander, 2008; Jeffrey, 2003; MacMynowski, 2007; Siedlok et al., 2015).	Interviews with engineer-non engineer research teams to explore important factors for cross-disciplinary collaboration (Borrego and Newswander, 2008).
	Negotiating compromises between the different researchers to reach a consensus (Boix-Mansilla, 2006; Klein, 2008).	Case study comparative analysis to test framework for describing integration (Bammer, 2008). Interview data from researchers from nine research networks (Boix-Mansilla et al., 2012). Interviews with 50 researchers from interdisciplinary research centres about their experiences of interdisciplinary work (Boix-Mansilla, 2006).
Boundary setting	Identifying defensible boundaries in order to capture the perspectives required by the research objectives, with consideration for the restrictions (e.g. funds, skills, resources, time) (Bammer, 2008).	Case study comparative analysis to test framework for setting legitimate boundaries (Bammer, 2008).
Facilitating interaction between researchers with different world views		
Supporting face to face interaction	Regular face to face interaction between researchers from different research fields supports successful interdisciplinary research (Cummings and Kiesler, 2007; Haapasaari et al., 2012; Heinze et al., 2009; Kabo et al., 2014).	Case study analysis using ethnographic methods (Haapasaari et al., 2012).
		Surveys of Principal Investigators of information technology projects to explore collaboration (Cummings and Kiesler, 2007). Analysis of factors supporting "highly creative" researchers (Heinze et al., 2009). Spatial network mapping and comparison to selected indicators of collaboration (Kabo et al., 2014).
Brokering connections	A central person who facilitates connections between the researchers can lead to collaborations (Siedlok et al., 2015).	Case study analysis using an ethnographic approach and interviews (Siedlok et al., 2015).
Intermediary outcomes − Social capital		
Communication skills, team working skills and a broad perspective	Skills to communicate successfully with experts from other research fields, having a broad understanding of multiple research fields, and having the ability to work effectively in a cross-disciplinary team facilitate collaborative interdisciplinary research (Borrego and Cutler, 2010; National Academy of Sciences, 2004).	Analysis of funded proposals for innovative graduate programmes in the US to identify the main learning outcomes academics anticipate being achieved from an interdisciplinary programme (Borrego and Cutler, 2010).
Trust	Trust between researchers is critical for cross-disciplinary collaborations and can be lost if credit is not fairly distributed (Borrego and Newswander, 2008; Siedlok et al., 2015).	Interviews with engineer-non engineer research teams (Borrego and Newswander, 2008).
	Tighter relationships between people indicate more trust and respect and greater access to assets embedded in the social network (Jha and Welch, 2010).	Analysis of survey data on research networks (Jha and Welch, 2010).

(*continued on next page*)

Table 2 (*continued*)

Evaluation criteria	Empirical findings supporting the criteria	Indicators and data sets used
Connectivity between researchers	Researchers affiliated to a research centre produce more co-authored interdisciplinary publications (Ponomariov and Boardman, 2010).	Analysis of authorship of publications from a research centre (Ponomariov and Boardman, 2010).
	Co-author publications capture only part of all the collaboration taking place (Heinze and Kuhlmann, 2008).	Analysis of authorship of publications and grants combined with interviews to better understand collaboration (Heinze and Kuhlmann, 2008).
A shared identity and shared values	A shared sense of the profile of scholars that belong in the group are important for recruiting the "right kind of people" to achieve successful collaboration (Boix-Mansilla et al., 2012; Siedlok et al., 2015).	Interview data from researchers from nine research networks (Boix-Mansilla et al., 2012).
Research and education outcomes – Knowledge and human capital		
New knowledge	New joint grants awarded are used as a proxy for success of a collaboration (Kabo et al., 2014).	Analysis of number of joint grant applications funded (Kabo et al., 2014).
	Co-author publications, proposals and grants indicate collaborative research taking place (Heinze and Kuhlmann, 2008).	Analysis of authorship of publications and grants combined with interviews to better understand collaboration (Heinze and Kuhlmann, 2008).
Quality of cross-disciplinary work	Interdisciplinary work is published in higher ranking journals and receives a greater number of citations indicating it could be of higher quality than mono-disciplinary work (Borrego and Newswander, 2008; Carr et al., 2017).	Comparison of citation rates for mono, multi and inter-disciplinary publications (Borrego and Newswander, 2008; Carr et al., 2017).
Professional skills	Doctoral training in an interdisciplinary programme develops interdisciplinary skills that the graduate applies in their future career (Carr et al., 2017).	Comparison of disciplinary nature of doctoral thesis with the disciplinary nature of post-doctoral position (Carr et al., 2017).

3. A framework for evaluating interdisciplinary research programmes

To understand interdisciplinary research, an evaluation framework is needed that can capture not only the variety of interdisciplinary outcomes emerging from a programme or project, but can also link them to their driving processes. The authors had previously conducted a review into evaluating stakeholder and public involvement in water management. Through case study evaluation and meta-analysis they identified numerous intangible, intermediary outcomes that resulted from "good" processes (Carr et al., 2012). Intermediary outcomes also indicated that tangible (e.g. resource management outcomes) will emerge (often at a later point in time). With this in mind, review of the literature containing empirically based findings on interdisciplinary research showed that processes, intangible intermediary outcomes and tangible research and education outcomes can be identified (Table 2). Interestingly, the processes align very well with the concept of "social learning". Intermediary outcomes can be related to "social capital" and tangible research and education outcomes relate to "knowledge and human capital". The literature review led to development of the conceptual framework of the dynamics of cross-disciplinary research development (Fig. 1) that is explained in detail in this section.

3.1. Context

The context in which an interdisciplinary project takes place is likely to be highly significant in determining the quality of its processes and is subsequent achievements (Heinze and Kuhlmann, 2008; Porter et al., 2006; Stokols et al., 2008). Context factors (also called antecedents) include personal values, goals and expectations, the physical environment, the bureaucratic setting (Stokols et al., 2003) and institutional support (Boardman and Corley, 2008; Heinze and Kuhlmann, 2008; Heinze et al., 2009; Ponomariov and Boardman, 2010). Institutional and funding arrangements act as facilitators and motivators that support interaction between collaborators (Amin and Roberts, 2008). As positive outcomes emerge, it is expected that there will be increased institutional support. At the same time, a history of successful collaboration between researchers is also likely to raise researchers' motivation and ability to collaborate further, and subsequently further increase outcomes (Borrego and Newswander; Stokols et al., 2012).

3.2. Social learning processes

Social learning as a framework provides an extremely promising model for evaluating the processes of cross-disciplinary research. Social learning theory pulls together various learning theories such as transformative learning (Argyris and Schön, 1978), learning as a social practice (Lave and Wenger, 1991) that is shaped by the cultural, social and historical context in which interactions between individuals take place (Lattuca, 2002), and Habermas's theory of rational discourse (Habermas, 1979) (for thorough discussion of social learning see Muro and Jeffrey, 2008; Reed et al., 2010). Social learning has become widely discussed in the environmental management field because of its anticipated capacity to lead to a shared understanding between different actors (an aspect of social capital, see 3.3), instill social change and enable collective action on issues that are complex and multi-faceted (Muro and Jeffrey, 2008). These broad aims correspond with those of cross-disciplinary research, and perhaps particularly to research concerned with natural resource management. Reed et al. (2010, p.1) propose that a social learning process must, "(1) demonstrate that a change in understanding has taken place in the individuals involved; (2) demonstrate that this change goes beyond the individual and becomes situated within wider social units; and (3) occur through social interactions and processes between actors within a social network." We have adapted these criteria to evaluate the programme's processes taking place at three different levels, the individual, the group, and the programme manager:

1) *The individual* – How do the programme's approaches generate a change in understanding at the individual level?
2) *The group* – How do the programme's approaches support the development of common interdisciplinary research practices?
3) *The programme manager* – How do the programme's approaches support social interaction that brings people together who have different world views?

3.2.1. Processes for individual learning

Several different aspects to individual learning are identified in the literature (Table 2). These include learning specific details about other fields, being able to understand the differences between the different research fields, as well as the limitations to each field, learning how to communicate ones research and to identify suitable collaborators.

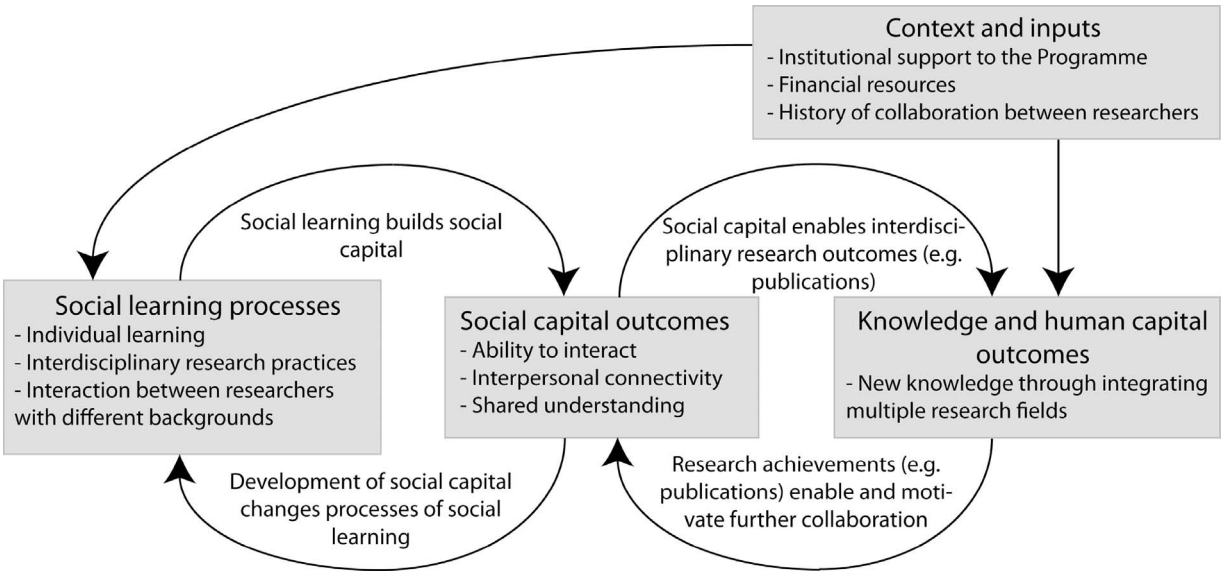

Fig. 1. Conceptual framework for exploring the development of cross-disciplinary research.

Learning would therefore be expected to precede the achievement of various intermediary outcomes. Such as the ability to communicate and interact with researchers from other fields, to reach some shared understanding and have a "shared interpretive horizon" (Hibbert et al., 2016), and to achieve connectivity between the different researchers.

3.2.2. Processes for developing shared interdisciplinary research practices

Interdisciplinary research practices relate to the way that a community of researchers from diverse research fields "do things together", craft an identity (Gherardi, 2009), and develop a unique working style and way of doing things (Boix-Mansilla et al., 2012). They would therefore be expected to precede the development of a shared group identity, shared values and shared understanding (intermediary outcomes) (Siedlok et al., 2015). Practice can be described as a set of doings or sayings that are aimed towards a particular purpose (e.g. preparing a research manuscript) (Nicolini and Monteiro, 2017). Groups of individuals perform and promote practices, for example, the format of meetings, the structure of papers and presentations, and the styles of communicating with each other. Interdisciplinary research practices are therefore strongly embedded in the norms of each of the disciplines being integrated and interdisciplinary researchers need to negotiate the new territory at the disciplinary boundaries by developing research practices specific for the interdisciplinary work they are doing (Castan Broto et al., 2009; Boix-Mansilla et al., 2012). By placing the practices themselves at the centre of a research enquiry (making them the unit of analysis) a deeper understanding of how interdisciplinary research practices develop and are sustained can be achieved (Nicolini and Monteiro, 2017). Empirically based research has identified a number of interdisciplinary research practices that include clarification, harnessing differences and managing potential conflict, and setting defensible boundaries to the research enquiry (Table 2).

3.2.3. Processes for facilitating interaction between researchers with different world views

By bringing diverse groups of researchers together it is expected that, i) information will be transmitted between them and each person will learn something new, and ii) they will deliberate with one another and develop more creative ideas together than they would have developed alone (Newig et al., 2010). Interaction could be considered to extend individual learning by bringing in the concept of "thinking together," whereby people interact together to guide one another through their understanding of the same problem (Pyrko et al., 2016). As such, it is expected to lead to new shared understandings (an intermediary outcome) because it enables researchers to recognise that someone thinks differently to them, or they think differently to others (see Gadamer, 2004 cited in Hibbert et al., 2016). Several studies have explored the role of face-to-face interaction to show that it is highly significant for achieving successful collaboration (see Table 2). Additionally, Siedlok et al. (2015) noted how a central facilitator who brokers connections between the researchers can also be important for achieving interpersonal connectivity (an intermediary outcome).

3.3. Intermediary social capital outcomes

Interaction, connectivity, shared values and understanding, and trust are elements of social capital identified in the interdisciplinary evaluation literature (Table 2). Higher social capital is expected to lead to a higher capacity to invest in collective activities to achieve shared objectives (Pretty, 2003; Putnam, 1995), that in this case might be joint publications. The ability of researchers to interact with one another and their connectivity to each other, trust between them, and the development of shared understanding, are expected to facilitate the development of knowledge capital (new interdisciplinary research findings) (Nahapiet and Ghoshal, 1998). Social capital is also expected to result from effective processes that cultivate learning, develop interdisciplinary research practices and generate interaction.

Shared understanding may be a particularly important intermediary outcome for interdisciplinary programmes and projects. This is because it has been suggested that interdisciplinarity may be of value not because it can address given problems, but because it can generate new questions that can then stimulate new approaches and practices to be developed to address the new questions (also called problematisation) (Barry and Born, 2013). Problematisation should evolve through the interdisciplinary practices of clarification, boundary setting, and harnessing differences that require critical conversations, debates and discussions on, for example, what is the problem that needs to be addressed, and who's theoretical framework is 'right'. These conversations, where someone realises that there are different ways of thinking about a problem or issue, are expected to be critical for generating new, shared understandings (Hibbert et al., 2016). They would be expected to precede the development of a cross-disciplinary joint research question (a tangible outcome) that all researchers feel is relevant and interesting to them and their research field, and which subsequently shapes their research endeavour leading to new interdisciplinary knowledge (Borrego and Newswander, 2008; Miller et al., 2008).

3.4. Knowledge and human capital outcomes

Every evaluation is shaped by the values of those it involves (Greene, 1997; Donaldson et al., 2010; Patton, 2008). Different people will have different objectives (Feller, 2006) as reflected by the evaluation literature (Table 2). Students may join an interdisciplinary programme because they want to extend their professional networks and increase their career opportunities, while university professors are likely concerned with grants and publications in leading journals, and funding bodies may want to see how the research benefits society at large, or whether there is "added value" from providing support to an interdisciplinary programme versus a disciplinary programme. One approach to identify the values that should shape the evaluation is to identify the people who will use the evaluation findings and then to include these users in the design of the evaluation (Patton, 2008). For this evaluation, the users were deemed to be the faculty of the programme who have responsibility for shaping and running the programme. The values and priorities of these people were obtained through two discussion workshops facilitated by the programme coordinator (held on 6 June 2012; 6 September 2012). These revealed that the faculty identify two aims for the programme: 1) to produce new knowledge through integrating multiple research fields; and 2) to produce graduates with the capacity to work across the disciplines to address society's water research and management needs.

The literature contains several examples of evaluations that measure the quantity and quality of new interdisciplinary knowledge according to joint grants, co-author publications and journal ranking and citation rates for interdisciplinary publications (Table 2). Assessing the impact of interdisciplinary training on graduate skills and careers remains would require further work but limited data suggest that interdisciplinary training during the doctorate leads to an interdisciplinary career after graduation (Carr et al., 2017).

4. Evaluation criteria, indicators and data sets to explore interdisciplinarity

The framework has been developed specifically to explore the interactions between processes, intangible intermediary outcomes and tangible research outcomes. Evaluation criteria, indicators and data sets are identified to capture the development of interdisciplinary research within a case study doctoral programme. Based on prior research (Table 2), criteria for each of the process and outcome aspects in the framework have been established (Table 3) and data sets to operationalise the criteria have been described (Table 4).

Data were collected using a mixed qualitative/quantitative approach that allows us to capture and describe not only what is happening, but also explore why it is happening (Campbell, 2011; Fazey et al., 2014). The evaluation is internal, as it has been conducted by the programme coordinator who has been working with the programme since it started in 2009. This introduces recognised advantages (understanding and knowledge of the people, their work and their interactions) and disadvantages (limited impartiality).

4.1. Social learning processes

4.1.1. Individual learning

Features of the programme that support learning at the individual level have been evaluated through semi-structured interviews in July 2014 with 12 students and graduates in the programme (six female and six male). Interviewees were asked about their learning experiences, about which topics they feel they understand and what has helped them develop their understanding. The first author conducted the interviews, took notes that were later transcribed, and conducted the analysis. Following the method given by Kitchin and Tate (2000), the transcripts were read several times to identify common themes that emerged in the data set. All comments relating to learning were brought together and trends, similarities and differences in views and experiences were identified. They were coded according to factors identified in the transcripts that support understanding: background in the topic, language and communication, and problem focused approach. Additionally, the content and structure of the courses in the study programme were examined by the evaluators to explore if the courses explicitly taught students how to integrate different fields of expertise. To complement the student perspective, the second author reflected on how students learn in his interdisciplinary course and the factors that support student development.

4.1.2. Developing shared inderdisciplinary research practices

To explore how interdisciplinary research practices develop in the programme, interviewees were asked about their experiences of doing interdisciplinary research and faculty were questioned about the challenges and strategies for interdisciplinarity they identified. Transcripts were coded according to broad themes that emerged on communication, awareness to programme activities and research and collaborators characteristics. The evaluator team also reflected on how the programme supports the development of the practices identified in the literature of clarification, harnessing differences and setting defensible boundaries.

4.1.3. Facilitating interaction between researchers with different world views

To explore how effective the programme's activities (Table 1) are perceived for supporting interaction between researchers from different fields, the 12 interviewees were asked to score each approach on a scale of one to seven (and give their reasons) according to the benefit they perceive to gain from each for conducting interdisciplinary

Table 3
Criteria developed for this evaluation and their descriptors.

Social learning processes	Social capital outcomes	Knowledge and human capital outcomes
Individual learning	Ability to interact	New knowledge through integrating multiple disciplines
Features of the programme that support cross-disciplinary learning.	Perceived ability of researchers to interact and communicate with those from other research fields.	Types of cross-disciplinary work produced in the Programme and individual progression from multi- to interdisciplinary work based on analysis of cross-disciplinary publications.
Developing shared interdisciplinary research practices	Interpersonal connectivity	
Features of the programme that generate interdisciplinary research practices.	Development of cross-disciplinary collaborative research through time based on authorship of publications.	
Facilitating interaction between researchers with different world views	Shared understanding	
Features of the programme perceived by participants to support cross-disciplinary collaboration.	Research questions in each student's thesis proposal that are addressed through bringing in theories or methods from more than one research field.	

Table 4
Data sets and measurable variables used to operationalise the evaluation.

Evaluation criteria	Data sets used for evaluation	Measurable variables
Social learning processes		
Individual learning	12 semi-structured interviews with students and graduates.	Factors students identify that support their understanding of different research fields.
	Lecturer reflection on learning in cross-disciplinary courses.	Factors that students and lecturers identify in cross-disciplinary courses that support learning how, why and what to integrate.
Shared interdisciplinary research practices	12 semi-structured interviews with students and graduates.	Places, strategies and practices for doing interdisciplinary research
	10faculty questionnaires. Evaluator observations of development of interdisciplinary research practices.	
Facilitating interaction	Scoring of programme activities by 12 students and graduates according to how each is perceived for supporting cross-disciplinary research.	Score allocated to each activity and reasons for the scores allocated.
Intermediary social capital outcomes		
Ability to interact	12 semi-structured interviews with students and graduates.	Perceived capacity of researchers to interact with experts from other fields.
Interpersonal connectivity	86 ISI journal publications where a member of the programme is the first author.	Proportion of cross-disciplinary publications (with authors from more than one research field) relative to mono-disciplinary publications.
Shared understanding	12 semi-structured interviews with students and graduates.	Processes described for developing cross-disciplinary research questions.
	10faculty questionnaires.	Number of thesis proposals stating cross-disciplinary research questions.
	36 thesis proposals 40 ISI cross-disciplinary journal publications	Number of cross-disciplinary questions leading to cross-disciplinary publications.
Research and education outcomes		
New knowledge through integrating multiple disciplines	40 ISI journal publications produced through cross-disciplinary collaboration.	Number of inter- or multi-disciplinarity publications, categorised using Huutoniemi et al.'s (2010) framework. Changes in types of publications though time at the individual level.

collaborative research (one being of low benefit and seven of high benefit). Further comments and reasons for the scoring from the transcripts were brought together to aid evaluator understanding of where and why interaction in the programme is perceived to be of greatest benefit for collaboration.

4.2. Intermediary social capital outcomes

4.2.1. Ability to interact

To assess how capable researchers are in their ability to interact with one another, each interviewee was asked how capable they feel in their capacity to interact with researchers from other research fields. The perceived capabilities were grouped according to three categories of highly confident, moderately confident and confident if given additional support that corresponded with the interviewees responses. Using researchers' perceived confidence in ability to interact across the disciplines introduces the assumption that perceived confidence corresponds to actual ability. While we can only speculate that confidence does correlate to ability, analysis showed that interviewees with a higher self-confidence in their ability to interact had received more extensive interdisciplinary training, thereby supporting their self-assessment (see 5.3).

4.2.2. Interpersonal connectivity

Joint publications have been used as a proxy for the connectivity between researchers from different research fields in the programme. Connectivity has been measured by first grouping each student and post-doc according to the research field of their primary supervisor. The 86 ISI indexed journal papers where a member of the programme was first author published between 2009 and 2015 were categorised as mono- or cross- disciplinary depending on the research fields of the multiple authors. Papers produced by authors from the same research field were categorised as mono-disciplinary. Papers produced by authors covering two or more research fields were categorised as cross-disciplinary. The proportion of cross-disciplinary publications compared to mono-disciplinary publications is used as an indicator of the degree of connectivity.

The operationalisation of the connectivity indicator makes several assumptions. Firstly, that each researcher can be placed within one research field category and that this field corresponds accurately to that of the primary supervisor. We recognise that researchers (particularly those working across disciplines) may not always identify themselves within a single field, but the work of each student in the programme strongly reflects the interests of their supervisors, therefore we feel comfortable with this assumption. Secondly, using co-authored papers as a measure of connectivity introduces the assumption that names on papers accurately reflect the actual team of collaborators, but this may not always be the case (Katz and Martin, 1997; Laudel, 2002; Wagner et al., 2011). Detailed analysis of each cross-disciplinary publication suggested that in three cases a co-author from a different discipline had been included although the work did not incorporate aspects of their specific research field (see Carr et al., 2017). However, discussion with the authors revealed that these co-authors were clearly involved in planning and shaping the work and defining the future directions of the interdisciplinary research. We therefore feel confident that the list of joint authors reflects a minimum level of interpersonal connectivity and imagine that a larger number of researchers have been engaged in each piece of work than is reflected by the author list.

4.2.3. Shared understanding

In this work, cross-disciplinary research questions are used as a proxy for shared understanding. To gain insight into how cross-disciplinary research questions are developed, each faculty member provided written comments describing how they develop such questions in July 2016. Analysis of the comments was conducted by the first author to identify the different approaches taken. This was coupled with the

comments relating to developing cross-disciplinary questions in the student and graduate interviews. Additionally, the thesis proposals produced by each student in the first six to twelve months of their doctorate were examined to identify the presence of cross-disciplinary research questions. Typically each research proposal outlines three or four planned publications, states the research question that the work will address and the researchers who will be involved. Each research question in each thesis proposal was examined by the first author and categorised as either mono-disciplinary or cross-disciplinary depending on whether it planned to be addressed by including the phenomena, theories or methods from more than one research field (Szostak, 2007). In some cases the planned cross-disciplinary collaboration involved similar research fields, for example, one student planned to develop a resource management model in Paper 1 (mono-disciplinary) and apply it to the new and different setting of groundwater pollution in Paper 2 (cross-disciplinary). While in other cases more ambitious attempts at linking two very different research fields were planned. For example, a structural mechanics student planned to develop a method for reducing model computational demands (mono-disciplinary) and subsequently apply it to data in a microbiology setting (cross-disciplinary). The assumption that cross-disciplinary research questions are indicative of shared understanding has been made because the thesis proposals are developed in close collaboration with the supervisor(s). The presence of cross-disciplinary questions is taken to suggest that mutual understanding has been achieved between the student and the co-supervisors (from different research fields) as a base for the planned cross-disciplinary research.

4.3. Knowledge and human capital outcomes

4.3.1. New knowledge

To explore the development of interdisciplinary research findings we have categorised the cross-disciplinary ISI indexed publications (n = 40) according to their type of cross-disciplinarity using a framework developed by Huutoniemi et al. (2010) (Table 5). The content (introduction, methods, results/discussion, conclusion/significance, references) of each cross-disciplinary publication was examined and categorised by the first author. Only ISI journal publications have been included to ensure each piece of work evaluated is of peer reviewed quality and to facilitate the categorisation process. The results of the categorisation were then examined to explore: i) whether interdisciplinary or multidisciplinary research dominates the research taking place in the programme, with the expectation that effective processes will lead to the development of intermediary social capital outcomes and to interdisciplinary work rather than multi-disciplinary work; and ii) whether researchers' publication profiles show development from multi-disciplinary work to interdisciplinary work, with the expectation that individual learning and development of interdisciplinary research practices support a shift from encyclopedic multi-disciplinary work towards theoretical interdisciplinary research.

The strength of using Huutoniemi et al's (2010) framework is its ability to sort and categorise the highly diverse publications into a system that enables interdisciplinary analysis. However, Huutoniemi et al. (2010) note that different researchers may categorise a piece of work differently, in part because researchers rarely have expertise in all the different research fields covered by an interdisciplinary paper. In this study, the researcher conducting the categorisation was highly familiar with each piece of work as she had witnessed each one develop through numerous presentations and discussion meetings within the programme framework. Due to this extensive prior knowledge we feel confident that the categorisation is sufficient enough for exploring the nature of cross-disciplinarity in the programme.

5. Interdisciplinary development in the case study doctoral programme

5.1. Context

At the start of the programme each faculty member had some experience of working with at least one other faculty member through joint proposals, projects and papers. As such, the programme was effectively building on existing positive working relationships. The major funding for the student positions and education programme came from the FWF, but the University provided additional financial support for two PhD students, as well as joint office space and chose to create a new “Centre for Water Resource Systems” to host the programme which was attached to the office of the Vice Rector, suggesting considerable University support.

5.2. Social learning processes

5.2.1. Processes for individual learning

The answers given by interviewees about their learning experiences revealed that they placed considerable emphasis on their educational background in their ability to learn about the new research fields covered by the programme (75 percent of students reported being able to easily understand topics for which they had a prior background):

> I find biology the toughest because there is lots of jargon and I've no background in this. Structural mechanics was also a bit tough as there is a lot of maths, but I have a background in this so it was okay. I found the course on water resource systems and socio-economic concepts more about things in real life and so easier to understand. (S9)

> My background is in engineering and so I can understand hydrogeology, water quality, mechanics and remote sensing. I least understand microbiology. This was a good interdisciplinary course in microbiology but it's completed outside my field of expertise. Though my understanding is increasing through time. (S4)

> I have a pretty decent understanding of them all, even structural mechanics. It took longer to understand but when the people make the effort to communicate their subject well I can get a good understanding. (S7)

Students' enhanced ability to learn about a new field if they are familiar with it from their past studies has been reported by Lattuca et al. (2004) and is highly relevant because it creates a “knowledge bridge” that lecturers need to capitalise on by placing their fields'

Table 5
The characteristics of publications within each category of cross-disciplinary research (MD = multidisciplinary; ID = interdisciplinary). Based on Huutoniemi et al. (2010).

Category	Description
Encyclopedic MD	Sub-projects brought together around a topic. Multiple authors contribute sections that are only linked together by the problem.
Contextual MD	Problem focussed with an integrative background pulling material from lots of disciplines, but no integration of other disciplines in the methods or analysis. Or methods borrowed from one field to solve a problem in another field.
Composite MD	Division of labour approach. Different specialisations responsible for different sections of the research and write up.
Empirical ID	New or existing empirical data from lots of different fields integrated to solve an inter-disciplinary problem.
Methodological ID	Methods specifically developed to fit the inter-disciplinary research question being addressed.
Theoretical ID	Brings together concepts, models or theories from more than one field to develop a new theory.

knowledge in the context of each students background (Haapasaari et al., 2012). They do this, for example, through using examples from multiple research fields such as water flow and heat transport to demonstrate how numerical solutions and modelling approaches are the same irrespective of discipline (see Blöschl et al., 2012).

Learning the differences between research fields and their limitations is another element of learning identified in the literature (Haapasaari et al., 2012; Hibbert et al., 2016). During the symposia, students are encouraged to present not only their positive research successes and strengths of their methods or approaches, but to identify the weaknesses and be open about the set-backs and challenges that they have experienced. Learning to identify the limitations of one's own research field was not mentioned by any interviewee or faculty member. However, identifying the limitations of other research fields was noted to be important by one student and one faculty member in order to manage expectations:

> There's a contrast between my expectation of what they [the other research field] can provide and what they can actually provide. For example, I might think that remote sensing can solve my problem but actually it can only give me a limited amount of information. (S2)

Learning “how to learn” about other fields was identified in the interview data, although this was not explicitly seen in the empirically based literature (Table 2). Two interviewees described how their experiences in the programme have taught them “which questions to ask," to develop their understanding of other research fields:

> I've learnt the process. First I'm exposed to new stuff, I develop an understanding, then I talk to the people again, learn more and digest it, then go back to ask more questions. (S7)

> I feel very comfortable working in an interdisciplinary setting. For my PhD I get lots of exposure and get familiar with lots of disciplines. Being in a multidisciplinary environment in this programme means you learn how to talk to people in a non-technical way. It also teaches us what questions to ask to really learn what others are doing. (S9)

Similar to the findings of Olsen (2009), the quotes suggest that learning how to learn about other research fields is self-taught and comes through experiences of working directly with people from different research fields. As noted in the second quote above, communication plays a key part in this and is discussed in more detail in the next section.

An element of individual learning revealed in this case study that had not been previously identified in the empirically based literature (Table 2), are the processes for learning how, why and what to integrate. Four courses in the programme teach integrated water management, an interdisciplinary concept prevalent in water resource research. The content of these courses brings together different research fields (e.g. microbiology and water quality; hydrology and economics; resource management and water quality). The course on “Water resources systems and socio-economic concepts," is an example where students integrate knowledge from different disciplines as they learn how to identify and evaluate possible solutions to various water resource management issues or problems. This course introduces students to the concept of focusing on system performance as opposed to the performance of each interacting component of a water resource system. Through the analysis of possible infrastructure development plans, designs, and management or operation policies they learn how to use and integrate aspects of economics, environmental and ecosystem sciences, hydrology, and political and social sciences. They begin to appreciate how decisions made regarding the allocation and management of water typically have economic, social, and environmental impacts. The optimization and simulation tools used to identify and evaluate alternative possible decisions based on these multiple impacts come largely from the disciplines of operations research, systems engineering, and computer sciences. Through practice in model building and solution, beginning with relatively less complex problems and then advancing to more complex ones, perhaps including more uncertainty and more conflicts among stakeholder objectives, they begin to see how such methods might be useful in their own research, and their possible jobs once they graduate. Students of more quantitative water resource systems courses seem to learn best by continually practicing the art of identifying, and then analysing using a variety of different approaches, various water quantity and quality management problems. The more practice the more they seem to learn. As problems become more complex, students increasingly benefit from more group work involving teams of individuals from different disciplines.

5.2.2. *Processes for developing shared interdisciplinary research practices*

Several different research practices emerge in the case study analysis. Clear communication and clarification through questioning are specific practices that are developed through the programme symposia and the cluster group meetings where researchers from different research fields are brought together. Students are counselled on communicating using clear and simple terms, and acronyms are forbidden. They are encouraged to ask questions to seek clarification when they do not understand (or if they disagree with) the work or approaches being conducted by others. At the symposia, communication and clarification is supported by allocating 10–15 min for discussion after each 15 min presentation. Faculty and external advisors lead by example in questioning topics outside of their primary research field. Additionally, short co-speeches are given whereby someone from a different research field summarises the work and initiates questions following each presentation. At the cluster group meetings small groups of researchers from different fields take turns to present their work, question each other and hold extended discussions on each others' research.

Practices for harnessing differences, or bringing different ideas, interests and personalities together constructively, were more difficult to identify in the case study data set. There was a noticeable absence of comments relating to personal experiences of scientific debate, discussion and conflict suggesting that these rarely take place. However, interviewees did note that mutual respect, trust and open-minded personalities were important for interdisciplinary work suggesting that programme participants are aware that certain skills and characteristics are needed to bring together different disciplinary perspectives in a constructive way:

> To do interdisciplinary work you need mutual respect and understanding between the people. You need to listen to the other side's thoughts and opinions. With us, mutual respect existed, and this is rare to find. (S7)

> The people I work with are open to suggestions and experiments. They are easy to talk to, and agree to new ideas. (S9)

In the programme, each student must prepare and defend a thesis proposal to the entire faculty and student group in the first six months of their doctorate. One aim of this is to set a defensible boundary around the research enquiry that sufficiently captures the perspectives required by the research objectives, with consideration for the restrictions such as time, resources and data availability. By presenting the work plan to the entire group it is critically assessed and refined from the perspective of numerous research fields. This helps ensure that cross-disciplinary work that is conducted as part of the PhD is cutting edge in all disciplines it covers, and helps expose new collaborative possibilities between the faculty and students.

5.2.3. *Approaches for interaction*

The 12 interviewees were asked to score the approaches employed by the programme according to how helpful they perceived them for conducting interdisciplinary collaborative research. Joint study sites and joint supervision were perceived to be of the highest benefit (Table 6). Six of the interviewed students work in one of the

Table 6
Student scores for the benefit provided by each of the approaches applied by the programme for conducting interdisciplinary collaborative research (1 = no benefit, 7 = high benefit) Av. = mean.

Programme activity/Interviewee code	*S1*	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*	*S8*	*S9*	*S10*	*S11*	*S12*	*Av*	*Std Dev*	*Description*
Study sites		7		7			7		7	7	5	7	6.7	0.8	High benefit
Joint supervision	7			4		7	6	7		7	7	7	6.5	1.1	High benefit
Shared offices	4	7		5	6	7	7	7	6	5	6	3	5.7	1.3	Some benefit
Block courses	6	5	6	6	6	7	5	6	2	5	7	7	5.7	1.4	Some benefit
Social events	4	5	7	6		4	5	7	7	7	4	4	5.5	1.4	Some benefit
Advanced study programme	6			4	5		4	7		3	7	7	5.4	1.6	Some benefit
Basic study programme	6	5	5	6	4	7	4	6	2	7	6	6	5.3	1.4	Some benefit
Annual symposium	6	4	7	5	6	4	6	5	3	7	2	5	5.0	1.5	Neutral to low benefit
Cluster meetings	2	5		7	2	5	6	2	5	7	7	7	5.0	2.1	Mixed response, high to low benefit
Six month symposium	6	4	5	5	6	4	5	4	4	5	1	4	4.4	1.3	Neutral to low benefit
Seminar series	1	3	2	5	6	2	5	5	5	7	5	7	4.4	2.0	Mixed response, neutral to low benefit
Mean score allocated by each student	4.8	5.0	5.3	5.5	5.1	5.2	5.5	5.6	4.6	6.1	5.2	5.8	5.3		

programme's joint study sites and they have either produced or are working on publications with authors from different research fields. Interviewees described benefits of data availability, the opportunity to run experiments, research focus points where many people could explore different parts of the same system, and giving access to people, research money and equipment. One student described how working in the research catchment showed her first-hand how other research fields work and another noted how his research required field data collection that he was unfamiliar with but that he had been able to work with and learn from colleagues familiar with these methods in the study site. Similarly, the interviewees who scored the research cluster groups highly noted them as being good places for getting advice and feedback from people with different specialisations.

Eight interviewees had experience with being jointly supervised and all except one gave this a high score. Their comments showed joint supervision was valued for interdisciplinary work for aspects of information transmission and for deliberation as different supervisors brought in complementary knowledge and skills that lead to more creative research pathways. As one student explained about her recent interdisciplinary work:

> I have the support and different motivations of two different supervisors. This is crucial. The focus of Supervisor 1 is different to Supervisor 2… Supervisor 2 was very motivated [to get involved in the work] when he saw the data that showed something interesting was there. Supervisor 1 would have discarded the material for a paper. It is crucial to have both. (S6)

These observations suggest that facilitating interaction in an interdisciplinary research programme needs to consider more than just face-to-face interaction between researchers (e.g. through meetings or study groups). Support needs to be given for more intensive processes that bring people together to generate data, develop experiments, collaboratively explore different parts of the same system, or extensively discuss the research being conducted from its inception to its completion.

5.3. Social capital outcomes

5.3.1. Ability to interact

The interviews and faculty comments revealed that researchers in the programme recognise the importance and challenge of being able to understand and communicate successfully with colleagues from other research fields. All interviewees were asked how capable they felt in their capacity to interact with researchers from other research fields. Analysis of the responses showed that they related their self-confidence in their interaction abilities to different aspects of the learning processes (described in 5.2) indicating a strong link between individual learning and the ability to interact. These included being confident in their ability to reach a high level of understanding in other research fields, having an improved understanding of the integration between the different system components/disciplines, and being able to communicate successfully with others. Interestingly, the degree of self-confidence seemed to correlate to the stage of the researcher and the amount of interdisciplinary collaborative research they had experienced. Seven interviewees reported feeling very confident in their ability to interact across the disciplines (these were graduates, fifth year and second year students working in the Hydrological Open Air Laboratory), three interviewees felt reasonably confident (fifth year and second year students working at that time on mono-disciplinary topics) and two interviewees reported that they would feel confident if they would receive additional support and training (second year students):

> I feel quite capable interacting with people from other disciplines. I'm not scared at all and feel confident, provided that the fields are not too far away from my own field. There are many reasons for why I developed this − the extra knowledge from the courses, the shared courses, my past experience − I've always done interdisciplinary research. I know what to do to talk to people from other disciplines − so a bit of everything. (S6)

> [The programme] experience makes me reasonably comfortable working in interdisciplinary environments − in concentric disciplines i.e. those close to my field. There's a difference between knowing disciplines from the text book to cutting edge. Being in an interdisciplinary programme gives you confidence that you can reach cutting edge in neighbouring disciplines. (S4)

5.3.2. Interpersonal connectivity

A total of 86 ISI journal indexed publications where a member of the programme is the first author have been produced from October 2009 to December 2015. Analysis of the research field diversity of the authors shows that a total of 40 are classified as cross-disciplinary (the authors are affiliated with two or more different research fields) and 46 are mono-disciplinary (the publication has only one author or all authors are affiliated with one research field). Analysis shows that there has been steady progression through the duration of the programme towards a greater proportion of collaborations being across the research fields rather than within the research fields (Fig. 2). This culminates in a situation in 2015 where almost 70 percent of papers are cross-disciplinary indicating good connectivity between researchers from different research fields within the programme.

This positive progression towards higher interpersonal connectivity suggests that the collection of social learning processes are contributing to connectivity. Further analysis of the co-author teams show that most cross-disciplinary work results through student collaboration with joint supervisors, supporting student observations that joint supervision is an important process for cross-disciplinary research in doctoral programmes.

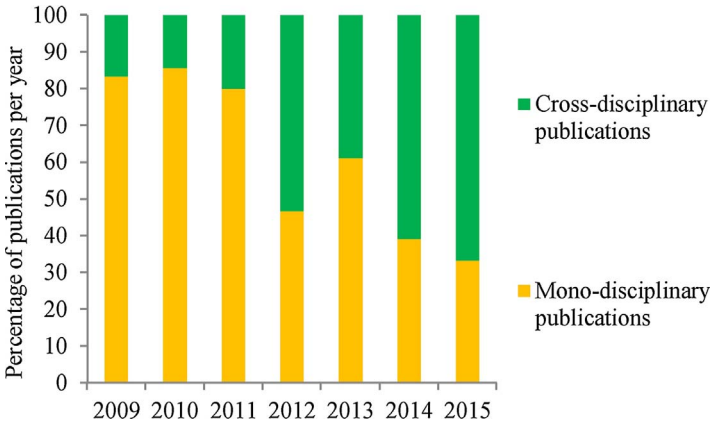

Fig. 2. Percentage of ISI journal publications where a member of the programme is first author (n = 86) according to whether more than one research field is represented by the author list (cross-disciplinary).

5.3.3. Shared understanding

Cross-disciplinary joint research questions are a key element of each students thesis proposal because they shape the research that will take place. Five students in the second year of their doctoral studies reported that identifying a cross-disciplinary joint research question was extremely challenging because additional time was needed to familiarise oneself with not only a basic understanding of another research field, but also the state of the art of that field:

> The challenges are that your research questions are derived individually. It is much more difficult and time consuming to come up with joint research questions. As you learn more you can think of more ideas but not at the beginning. (S9)

This suggests that individual learning to reach a high level of understanding of multiple research fields is needed to develop a shared understanding that translates into a cross-disciplinary research question. However, two students also argued that supervisors should clearly define the cross-disciplinary research questions at the start of the PhD:

> The main support strategy, or barrier if it's not there, is that you need support from your supervisors. The topics need to be interdisciplinary right from the start. Interdisciplinary is not especially supported in the programme. For example, if you want to work on something interdisciplinary you would need to work at the weekend on something that is at a tangent to your actual work. So you're expected to work on something interdisciplinary on the side. There's a time problem. There's not enough time. For example, the mechanics people aren't going to work on something with me just as a hobby. (S11)

The faculty were therefore asked about how they develop cross-disciplinary research questions. Five faculty members specifically reported that they did not find it challenging to develop such questions. Their responses showed that two approaches for developing joint cross-disciplinary research questions were commonly taken. In the “top-down” approach, the faculty member develops a question and then identifies suitable collaborators to engage in the work. In the “bottom-up” approach the faculty member starts with a broad research concept which they then discuss with a small group of collaborators from other research fields to develop the research question.

Four faculty members and four students noted that successful cross-disciplinary research collaborations required that the work is of mutual benefit to all researchers. This supports Amin and Roberts (2008) arguments that collaborative researchers need to feel interested, committed and loyal to addressing the shared problem. It would, therefore, be expected that the bottom-up approach would be preferred because it would have greater potential for co-producing research questions of mutual interest and benefit to all researchers. However, the faculty (who all have experience of successful cross-disciplinary collaborations) did not seem to favour the bottom-up approach which suggests that even top-down derived research questions can successfully engage collaborators in a manner that brings mutual benefits. This suggests that how the cross-disciplinary question is obtained is of less consequence than how the work proceeds to address the question. This finding is also somewhat in contrast to theory that expects truly interdisciplinary research to emerge when interaction takes place from the initial stage of problem framing (Barry and Born, 2013; Huutoniemi et al., 2010).

The interdisciplinary research practices of clarification, harnessing differences and setting defensible boundaries are likely to all play a role in developing questions and building on them to develop new knowledge that integrates the disciplines. For example, the authors of this paper have personal experiences of socio-hydrological modelling whereby social science is coupled with hydrology to build mathematical models that describe the interaction between floods and people. To do this, participants in multi-disciplinary research team use questioning and clarification to uncover each other's assumptions and to capture as fairly as possible the different priorities of each researcher. They negotiate which theoretical processes must be included and which could be omitted in order to reach agreement on the boundaries of the research. Importantly, the practices employed for developing shared understanding take place throughout the entire research process, from developing the research question to submitting and revising the publication.

The case study data show that shared understanding (as measured using cross-disciplinary questions) does seem to lead to new interdisciplinary knowledge. Analysis of 36 PhD thesis proposals showed that in 25 proposals, cross-disciplinary research questions were identifed. Eighteen of these proposals were by students being jointly supervised by faculty in the programme. This indicates that in these cases joint understanding between the co-supervisors had been achieved. It also further demonstrates the importance of joint supervision for cross-disciplinary research. Of the 25 students with cross-disciplinary research questions, 14 subsequently produced cross-disciplinary publications. Two students produced only mono-disciplinary publications and nine had not yet achieved their first publication at the time of evaluation. This suggests that cross-disciplinary research questions planned early in the doctorate supports the production of cross-disciplinary publications.

5.4. Knowledge and human capital outcomes

Forty ISI indexed cross-disciplinary journal publications where a member of the programme is first author were produced between 2009 and 2015. These publications are considered to represent the production of new knowledge that is a direct result of integrating multiple research fields. Each publication was categorised according to Huutoniemi et al.'s (2010) framework (Table 5) which revealed that

more than half of the cross-disciplinary publications (21) involved empirical interdisciplinarity (ID). This suggests that combining empirical data from different research fields is a common strategy for doing interdisciplinary work. Eight papers were categorised as methodological interdisciplinary and report how a new method or model had been developed or extended specifically to address a research need that stems across more than one research field. One paper was categorised as theoretical interdisciplinary, and three as mono-disciplinary. Pure multidisciplinary (MD) papers formed the minority of cross-disciplinary work (seven papers), perhaps suggesting that researchers favour interdisciplinary work or that multi-disciplinary work is more difficult to get published.

It is interesting to look at how the nature of cross-disciplinary publications changes through time at the individual level. Nine doctoral students published more than one cross-disciplinary publication. It may be of relevance to note that seven of the highly-interdisciplinary students are female suggesting that there may be a gendered aspect to cross-disciplinary research that has also been observed by other researchers (Leahey, 2006; Millar, 2013; Mills et al., 2011; Mitrany and Stokols, 2005; Rhoten and Pfirman, 2007; van Rijnsoever and Hessels, 2011). Analysis of the papers produced by the nine students shows that for six of these students the interdisciplinary nature of the publications changed as the research progressed (Table 7). It would be expected that as researchers become more familiar with the state of the art in their own and other research fields (individual learning), become more familiar with interdisciplinary research practices (clarification, harnessing differences and setting defensible boundaries) and encounter one another more often (interaction) they increase their social capital (develop their abilities to interact with one another, are more connected to each other, and are able to develop shared understanding). This increase in social capital would be expected to lead to a shift from multidisciplinary work such as contextual MD where they apply an existing model or approach to a new setting, towards empirical ID where they integrate different types of data, on to methodological ID to develop a model or approach specifically to address their research needs, and ultimately theoretical ID where a new interdisciplinary theory is developed. Although the data set is small, we believe it is of note to observe such progression to varying extents in the cases of Students 1–6 (in Table 7). In these cases, author analysis shows that the team of collaborators has enlarged or changed with each publication, bringing in new areas of specialisation, and further indicating that social capital is increasing through time.

6. Recommendations and extensions to the framework

The aim of this work was to identify the processes and factors that support interdisciplinary research outcomes based on the experiences of an established interdisciplinary doctoral programme. The objective is to provide recommendations to others and to ourselves about how the quantity (and quality) of interdisciplinary research outcomes can be increased. The proposed framework has proved to be very useful for understanding the development of interdisciplinary research in a case study programme. Each process element identified in the framework seems to contribute to building cross disciplinary social capital, and this social capital does seem to be critical for producing new interdisciplinary knowledge and skills (knowledge and human capital).

Table 7
Nature of the publications for students that produced more than one cross-disciplinary publication (MD = multidisciplinary; ID = interdisciplinary).

Student	Sex	Paper 1	Paper 2	Paper 3
1	Female	Empirical ID	Empirical ID/ Methodological ID	Empirical ID/ Methodological ID
2	Female	Empirical ID	Empirical ID	Methodological ID
3	Female	Contextual MD	Contextual MD	Empirical ID
4	Female	Contextual MD	Empirical ID	Empirical ID
5	Female	Composite MD/ Empirical ID	Methodological ID	Contextual MD
6	Female	Empirical ID	Empirical/ theoretical ID	
7	Female	Methodological ID	Methodological ID	
8	Male	Empirical ID	Contextual MD	
9	Male	Methodological ID	Methodological ID	Empirical ID

6.1. Recommendations for other interdisciplinary programmes

The case study programme analysed in this study is in its eighth year and has evolved in this time to reach a point where cross-disciplinary collaborative publications form the majority of the papers being produced. Based on the experiences of our programme captured by the evaluation data presented, several recommendations for other programmes can be made that may help them achieve interdisciplinary research outcomes more quickly than we have done ourselves.

Firstly, different aspects of learning have been identified that need to be considered and supported: i) learning about new research fields, ii) learning the differences between research fields and their limitations, iii) learning how to learn about other fields, and iv) learning how, why and what to integrate. Features that support learning identified in this study include group learning, building on existing knowledge, learning by doing and practicing the art of analysing different problems with different approaches. Further work would be needed to extend this further and develop beyond the simple conceptualisation of learning that is used in this study. There is an extremely wide body of literature on these aspects to build upon and explore in more detail how different elements of learning contribute to doing interdisciplinary research (for example, Gherardi and Nicolini, 2002; Hibbert et al., 2016; Lattuca, 2002; Lattuca et al., 2004; Lave and Wenger., 1991).

Secondly, our experience has identified several interdisciplinary research practices that have emerged, that with hindsight could have been made explicit, encouraged and supported from the onset of the programme. For this programme these include i) clear communication and clarification through questioning, ii) practices for harnessing differences that require mutual respect, trust and open-minded personalities, and iii) setting defensible boundaries around the research enquiry. These practices provide a valuable starting point but they could be further developed and extended for other programmes in future work. Additionally, work that specifically explores how the practices of successful interdisciplinary researchers contribute to research success would be highly beneficial. Different categorisations may also be useful, for example, individual practices and group practices (Siedlok et al., 2015).

Thirdly, places for interaction between researchers with different world views play an important role, along with individual learning, for developing connectivity between researchers. As other studies have shown (Table 2), face-to-face interaction is extremely important for facilitating collaboration. But this study shows that for interdisciplinary collaboration to lead to joint publications, more intensive processes are needed. In this programme these are provided by joint supervision and shared study sites that bring people together to extensively discuss their topics and collaborate on data collection, model development or experiment design. Comparing interaction approaches and outcomes from different interdisciplinary programme case studies would be an interesting area for future work.

6.2. Recommendations for our programme

The evaluation has identified several areas where additional support may enhance interdisciplinarity. As mentioned, joint supervision is a key driver of interdisciplinary research suggesting that every student in the programme should be jointly supervised. Identifying the shared interdisciplinary research practices at the programme level (e.g. clarification), and making them explicit to programme participants might

help them recognise how a practice can benefit their research and how they can further develop this practice as an individual and a community.

There is some evidence to suggest that developing the practice of harnessing differences may lead to considerable benefits. The data show a notable absence of debate, discussion, and scientific conflict in the programme. Such debate would be expected in the process of learning the limitations of one's own discipline and clarifying ones position and ultimately precede the development of new understandings (Hibbert et al., 2016). The lack of debate and scientific conflict may be due to the close disciplinary distance between the research fields involved in this case study. While this may make understanding and communication easier than for fields with wide disciplinary distance such as those from the natural and social sciences, it may also reduce the potential for discussion. For example, critical conversations are common practice in the social sciences, which proceed by "opening up debate," through recognising and embracing the many different 'truths' that exist. While the natural sciences and engineering have been described as high-consensus disciplines where there is strong agreement on the criteria for "truth" (Borrego and Newswander, 2008). They tend to proceed by "closing down debate," through reaching consensus on the 'facts' (Redclift, 1998). Further work (and experimentation) in the programme to explore how constructive, discursive practices can be brought into an interdisciplinary science and engineering setting and their subsequent impacts on generating interdisciplinarity would be extremely interesting and valuable.

6.3. Limitations and extensions to the framework

The complexity of the system means that a reductionist approach has been taken and many extremely deep and complex elements (such as learning, problematisation, interaction and connectivity) have been simplified, based on existing theoretical and empirical research, for the evaluation framework we have designed. There is therefore much space for development, refinement, improvement and extension.

One limitation to the framework is that indicators of social capital are based on proxies and there are assumptions associated with each that limit the conclusions that can be made. For example, connectivity as measured by co-authored publications may not reflect the true diversity of interactions. A more comprehensive measure of shared understanding could also be developed that captures shared methods, shared models or shared data sets. It would also be important to capture trust, a key element of social capital, in future work. Trust between programme researchers and their research fields is likely to evolve with individual learning, interaction and the development of shared research practices and subsequently support shared understanding and research outcomes (such as publications).

This evaluation has somewhat assumed that all researchers are equally interested and motivated to work across research fields. Prior work has suggested that personal characteristics such as risk taking behavior, an inquisitive nature, flexibility, commitment and patience influence an individuals' decision to do interdisciplinary work (Morse et al., 2007; Siedlok et al., 2015). Researchers might also choose to work across the disciplines because they enjoy the challenges and find it personally and professionally rewarding (Castan Broto et al., 2009; Heinze and Kuhlmann, 2008). The role of personal characteristics would need to be captured to more fully understand how processes lead to intermediary social capital and research outcomes. Exploring aspects of personality, and also gender, that give a propensity for interdisciplinary research would be interesting in future work.

Additionally, by measuring new knowledge using peer reviewed publications in ISI indexed journals we are limited in the variety of different knowledge capital that the programme has created. Reports, presentations, book chapters and conference papers are also knowledge capital that could be captured in evaluation. It would also be important to develop new measures to capture human capital in terms of graduate interdisciplinary skills. This remains an elusive area despite prior attempts by the authors (see Carr et al., 2017).

7. Conclusions

This work attempts to address some of the many gaps in our understanding of the workings of interdisciplinary research programmes. To do this, an evaluation framework has been developed based on social learning processes, intermediary social capital and knowledge and human capital outcomes.

Our results show that processes to support individual learning, develop shared interdisciplinary research practices, and facilitate interaction between researchers with different world views increase the connectivity between researchers, enable them to interact with one another and provide a platform on which shared understanding can be built. These intangible, intermediary social capital outcomes seem to lead to tangible knowledge outcomes (interdisciplinary publications). The evaluation framework demonstrates that interdisciplinary research and education is a process that involves various stages before research outcomes are achieved. This work illustrates this process and may be of value for securing the longer term commitment of interdisciplinary programme funders, managers and participants. More importantly, some process recommendations or "short cuts" have been identified that may support younger programmes, or those struggling to achieve interdisciplinary results. Broad process recommendations include supporting the different aspects of individual learning, identifying and making interdisciplinary research practices explicit and ensuring interaction between researchers is intensive.

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