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Transitions in urban water management and patterns of international, interdisciplinary and intersectoral collaboration in urban water science

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A B S T R A C T

Practitioners and scientists dealing with urban water management call for a transition to adaptive regimes. Transition management theories claim that to induce transitions, new forms of research are necessary which cut across traditional disciplinary, organizational and sectoral boundaries. Are such current calls for collaboration reflected in a fundamental change in scientific practices at the international level? This paper explores whether we witness cross-boundary interactions in professional networks and changes in the knowledge production towards more collaborative patterns in urban water science. To this end, we investigate both the professional interaction network at an international congress and the development of scientific output over the last two decades, using social network and bibliometric techniques. The results suggest that the professional interactions indeed reflect the cross-boundary interactions needed for a transition. However, the emerging patterns in scientific output do not indicate an actual system level shift towards a new mode of knowledge production.

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1. Introduction

Urban water management – the practice of managing the urban water cycle as a whole in coordination with the hydrological water cycle – is an increasingly complex, uncertain, multifaceted, and knowledge-intensive challenge (Klein, 2004; Van der Brugge et al., 2005; Brown et al., 2011; De Graaf et al., 2011). Trends such as explosive growth of urbanization, mismanagement of water resources, growing competition for the use of freshwater, and degraded sources by pollutants contribute to this complexity (Tejada-Guibert and Maksimovic, 2003).

For water management in general, so called adaptive regimes are perceived as crucial for a meaningful response to complexity and uncertainty (Pahl-Wostl, 2007). This also goes for urban water challenges, where concepts such as adaptive urban water management, water sensitive urban design, sustainable urban drainage systems, low impact development, and integrated urban water management have been developed (De Graaf et al., 2011). Expertise in adaptive urban water regimes is, almost by definition, interdisciplinary and intersectoral (Maksimovic and Tejada-Guilbert, 2001; Keath and Brown, 2009; Brown et al., 2011). Urban water management requires knowledge from many different disciplines, as well as the cooperation of a wide range of stakeholders. No single actor or discipline can solve complex urban water problems alone.

As such, urban water management reflects broader trends in the management of public goods, were one can witness more generally a call for transitions (Elzen et al., 2004; Van der Brugge et al., 2005; Loorbach and Rotmans, 2006). Transition management aims at moving socio-technical systems in areas like health, energy, infrastructure, and environment from one equilibrium to another. Transitions are characterized by multi-phase, multi-actor, and multi-level processes, which challenge transitional causal understandings of relationships within the socio-technical systems (Loorbach, 2007; Brown et al., 2011). As a result, programmatic studies on transition management often ask for interdisciplinary or transdisciplinary research (Bunders et al., 2010).

Such calls for a different kind of scientific research concur with ideas on new modes of knowledge production (Gibbons et al., 1994; Nowotny et al., 2001) and post-normal science (Funtowicz and Ravetz, 1993) from the sociology of science. The quintessence of these ideas is that scientific research shifts from traditional 'Mode 1', discipline-based knowledge production within academic institutions toward a new 'Mode 2' knowledge production which is interdisciplinary, cross-boundary, and includes scientists, engineers, designers, policy makers, NGOs and other stakeholders.

At the conceptual level, transition theories link characteristics of transition processes and the need for new knowledge production (Loorbach, 2007). It is unclear, however, whether we can indeed empirically observe such a shift to new modes of knowledge production at the system level. The aim of this paper is to assess if there is a transition in the field of urban water science (UWS) by examining two key areas: cross-boundary social interactions in the professional community and collaborations in research publishing. Specifically, our research questions concern:

(1) To what extent do we see cross-boundary interactions between professionals and researchers in the urban water management community? How does the level of cross-boundary interactions compare to other fields in water research?
(2) To what extent are cross-boundary interactions within the professional interactions reflected in more collaborative work in research publishing? More specifically, to what extent do we find an increase in interdisciplinary, intersectoral and international collaboration in scientific knowledge production?

In Section 2 we describe the congruence in the ideas on transitions in adaptive urban water management and in collaboration patterns in scientific research. This enables us to articulate our research questions more systematically. In Section 3 we explain how the data have been collected and which methods have been used to answer the research questions. We present the results in Section 4. In Section 5 we interpret and integrate our findings. In Section 6 we present our conclusion, discuss the implications and assess the limitation of our study.

2. Transition theory and new modes of knowledge production: parallel trends

Since the 1970s, there has been a shift from a technocratic water management style to the current practice of adaptive and participatory water management (Loorbach and Rotmans, 2006; Van der Steen, 2007). A typical example of this change is the SWITCH project, which induced transitions in urban water management in twelve delta cities, which all are threatened by climate change (Howe et al., 2011). A transition can be understood as socio-technological co-evolution processes leading to a fundamental structural shift in the way societal systems operate. Present-day transitions often aim at more sustainable production and consumption regimes in areas like energy, transport, food and water (Geels, 2002; Rotmans and Loorbach, 2010). Martens and Rotmans (2002) claim that a transition is the result of developments in structural, cultural and practical changes. Structural transitions imply changes in the ways how individuals organize themselves, either physically, institutionally, or economically. Cultural transitions mean changes in the ways of thinking and perceptions. Practical transitions are the changes in the way how individuals behave (Rotmans and Loorbach, 2010; Van den Bosch, 2010). The transition paths are highly non-linear, because these changes are intertwined and influence each other in a similar way as a set of gears reinforce and interlock with each other. Within transition processes, the development of niches is seen as crucial (Kemp et al., 1998; Geels and Schot, 2007) and often the leverage point for transition management (Raven et al., 2010).

Niche development is often induced by new innovations, new knowledge development and learning processes between heterogeneous actors (Hermans et al., 2013). Scientists may have a key role in transition processes by developing new tools and practices and sustaining learning processes, but they have to adapt their research substantially. Traditional theories and models associated to ‘the linear model’ for the science-practice interrelation cannot fully address complex societal problems, nor provide the integrated knowledge necessary to develop sustainable production and consumption regimes. A diverse range of modern literature from different disciplines has triggered a debate about the changing nature of knowledge systems. Gibbons et al. (1994) have coined the idea as a fundamental change from Mode 1 (homogeneity, unidisciplinary, largely university-based type of science) toward Mode 2 (applied, transdisciplinary, heterogeneously distributed networks based science). New styles of scientific activities have been developed as post-normal science (Funtowicz and Ravetz, 1993), in response to challenges in environmental policy. These scholars strived to demonstrate an underlying fundamental shift in how knowledge is created, diffused, and used in the reflexive relationship of science and the knowledge society.

Ideas on managing transitions in adaptive or integrated urban water management and ideas on new modes of knowledge production have in common that they call for a change in ways of organizing, working and thinking. We examine this change along three dimensions of collaboration: interdisciplinary collaboration, intersectoral collaboration, and international collaboration.

2.1. Intersectoral collaboration

The first shared notion is intersectoral collaboration. Urban water management is becoming a responsibility of a growing variety of institutions and the boundaries between the societal sectors of university, industry, and government are blurring. Problems in urban water management increasingly address issues of health, energy, infrastructure, environment, etcetera. The problems are characterized by significant complexity, high stakes for a diversity of involved actors, structural uncertainty and inefficient governance (Klein, 2004; Van der Brugge et al., 2005). From a socio-ecological system perspective, enacting adaptive governance to invoke a transition relies on collective actions of diverse actors at multiple organizational levels, which can be pursued through informal and formal networks (Folke et al., 2005; Brown et al., 2013).

Gibbons et al. (1994) argue that Mode 2 knowledge production is heterogeneous and contextualized, implying that scientists have to collaborate closely with non-scientists. This is also labeled as transdisciplinary, problem-oriented research, implying that boundaries between university, industry government, and society are fading (Klein, 2008; Hirsch et al., 2008). Universities lose their role as unique knowledge providers. Their focus changes from knowledge transfer to co-production, incorporating the needs of stakeholders in agenda setting and placing stronger emphasis on the usefulness and relevance of results (Hessels and Van Lente, 2008).

2.2. Interdisciplinary collaboration

The second shared notion is interdisciplinary collaboration. In contemporary adaptive urban water management, internal integration of different water domains such as water supply, stormwater management, wastewater collection, wastewater treatment and wastewater reuse is an important feature (Tucci et al., 2010). Each of these domains comes with its own interests and expertise, and – in other words – represents a specific water management discipline. Also, external integration of water with other policy fields such as health, energy, infrastructure, and environment is found necessary to address the interconnected, complex nature of urban water systems (Loorbach et al., 2010). This implies that for developing new adaptive urban water management systems knowledge from different disciplines has to be integrated.

In Mode 2, knowledge is produced within a context of application, by which scientists cross a range of theoretical and methodological perspectives to solve problems (Nowotny et al., 2003). Research that uses knowledge from different disciplines, but also integrates and synthesizes different perspectives to advance the understanding of problems, is often referred to as interdisciplinary rather than cross-disciplinary or multidisciplinary (Van den Besselaar and Heimeriks, 2001; Lyall et al., 2011; Wagner et al., 2011). Sometimes the terms interdisciplinary and cross-disciplinary or multidisciplinary are used somewhat interchangeably (Jeffrey, 2003; Cummings and Kiesler, 2005). All these approaches require participants from different scientific disciplines to work together and integrate knowledge (to a different extent) from their respective domains to create new knowledge, and thus serve broader goals. This is especially encouraged for addressing so-called wicked problems (Rittel and Webber, 1973).

2.3. International collaboration

International collaboration is the third shared notion. The need for international collaboration is ambiguous in both fields. On the one hand, urban water management has become an international issue, because of the importance of urban water management for society and environment at large. Countries have begun to realize that it is important to learn from experiences in similar or somewhat different contexts (Saleth and Dinar, 1999; Loorbach and Rotmans, 2006). We find similar tendencies toward internationalization in science. Many studies have demonstrated the rise of international collaboration in science and technology (Wagner, 2005; Wagner and Leydesdorff, 2005). This trend continues to grow in volume and importance.

It must be noted, though, that a tight cooperation with local actors is deemed essential for effective urban water management activities. Projects in new urban water management emphasize the importance of local participation. We find the same in science. The core of co-author networks in science remains localized: scientists are more likely to publish with other scientists within the same region, country, and linguistic area (Hoekman et al., 2010).

3. Data and methods

We first look at professional interactions during the IWA World Water Congress & Exhibition 2012 organized by the International Water Association (IWA). We assume that when participants attend the same topic-oriented congress sessions there is a potential for meaningful interactions. Next, we move from a rather static description of the network of session attendance to a more dynamic approach that takes into account changes in the nature of scientific collaboration. Using bibliometric indicators, which are commonly used to measure and analyze the cognitive and social structure of scientific research (Hicks and Katz, 1996; Mishel et al., 2003; Porter and Rafols, 2009), we explore emerging trends in research publishing.

3.1. Data and methods

3.1.1. Congress co-attendance network

For analyzing professional cross-boundary interactions, we constructed a co-attendance network, showing the extent to which participants from different types of organizations attended the same workshops at the IWA World Water Congress & Exhibition 2012. The congress is a global gathering of water experts and professionals, which took place in Busan, South Korea in September 2012. Participants were equipped with a smart card which checked them in when they entered a topic-oriented session on the congress venue. IWA, the congress organizer provided us with the participant's profile information and the detailed records about who attended which session at what time. This allowed us to construct co-attendance networks and analyze to what extent participants from different sectors (science, industry, and government) attended the same sessions. The IWA World Water Congress & Exhibition 2012 covered almost all aspects of water research, attracting a good number of professionals from science, industry, and government. A total of 1581 participants attended 198 specific congress sessions. A water expert from the congress classified these 198 sessions into 'urban water science', 'microbial ecology', 'biotechnology' and other issues. The participants' profile was analyzed based on the organizations they come from.

The co-attendance network connects individual participants based on their participation in congress sessions. Participants are connected by an edge if they attended one or more of the same congress sessions. The weight of an edge indicates the number of sessions co-attended by a pair of congress participants. Co-attendance does not mean that participants actually communicated. The assumption is that participants who visit the same sessions are more likely to communicate than participants who go to different sessions.

Using the community detection algorithm of Blondel et al. (2008), participants were clustered into communities. This is a heuristic method based on the optimization of modularity. It identifies clusters of nodes in the network that are more densely connected to each other than to nodes in other clusters. Blondel et al.'s method has been used, for example, to find topics in information networks and cyber-communities in social networks. Participants in the same communities are more likely to attend the same sessions – and possibly communicate – with each other than with congress participants in other communities. The network is visualized using Gephi (Bastian et al., 2009) software for large network analysis. In Gephi, we created graphs using the force atlas layout with attraction distribution, a special force-directed algorithm. The attractive force is distributed along outbound links. This tends to push hubs at the periphery and put authorities more central.

3.1.2. Bibliographic data

For analyzing collaboration patterns in UWS, we constructed a database from the five citation databases of Thompson Reuters ISI Web of Science (WoS).[1] The first exploratory task was to find meaningful keywords related to UWS. We consulted a number of experts in drawing up a list of relevant keywords (Appendix A) representing the fields of UWS. The list was used to define search terms, based on which we collected a total of 24,450 publications from the WoS spanning the period from 1990 to 2012. We used the SAINT toolkit (Somers et al., 2009) to parse raw bibliographic data into a relational database for analysis.[2] The database does not contain every single publication on UWS but is sufficiently representative to explore aggregated patterns.

3.2. Indicators, units of analysis and measurements

Table 1 summarizes the properties, indicators, and units of analysis used to answer the question to what extent there has been a change in interdisciplinary, intersectoral and international collaboration.

[1] WoS is a comprehensive bibliographic database, including five citation database: Science Citation Index Expanded, Social Sciences Citation Index, Arts & Humanities Citation Index, Conference Proceedings Citation Index-Science, and Conference Proceedings Citation Index-Social Science & Humanities.

[2] http://www.rathenau.nl/en/themes/theme/project/bibliometric-software-tools/saint.html.

Table 1
Mixed-indicators model for identifying collaboration in knowledge production.

Dynamic properties of knowledge production processes	Indicators	Unit of analysis
Growth rate	(a) Absolute growth rate: the number of UWS publications per year (b) Relative growth rate: the number of UWS publications per year divided by the number of all WoS publications per year	Field
International collaboration	(a) National diversity: the variety and balance of the nations involved in the whole UWS publications per year (b) International collaboration: the percentage of articles co-authored by authors from more than one country	Field/individual papers
Interdisciplinary collaboration	(a) Disciplinary diversity: the variety and balance of the disciplines (WoS categories) distributed in the whole UWS publications per year (b) Interdisciplinary collaboration: the percentage of articles published in interdisciplinary journals	Field/individual papers
Intersectoral collaboration	(a) Sectoral diversity: the balance of societal sectors distributed in the whole UWS publications per year (b) Intersectoral collaboration: the percentage of articles co-authored by authors from more than one sector (c) Co-authorship matrix	Field/institutions/individual papers

We used different indicators and applied them to different units of analysis (the field of UWS, institutions active in research, and individual papers) to test each of the three collaboration types.

We have measured the international collaboration based on the country of the co-authors' affiliations. For example, if a Dutch researcher lives in Sweden and works for a Swedish organization and co-authors with another Dutch researcher who works for a Dutch organization, the co-authorship will be considered as an international collaboration. We have looked for the presence of different countries in the research address field of publications and have analyzed the diversity of countries involved in publishing at a field level and the percentage of publications co-authored internationally.

There is no common definition of interdisciplinarity. Wagner et al. (2011, p. 16) generally describe interdisciplinary research as integrating "separate disciplinary data, methods, tools, concepts, and theories in order to create a holistic view or common understanding of a complex issue, question, or problem." The definition has been operationalized by investigating the variety of co-authors (if co-authors are specialized in different disciplines), the variety of citations (if the knowledge is integrated from different disciplines), or the nature of journal in which the article published. The last indicator best suits our information availability. We have analyzed the WoS categories assigned to the journals in which the UWS articles appeared. Using the Journal Citation Report of 2010, Rafols et al. (2010) clustered the WoS categories into 19 macro-disciplines. We define an interdisciplinary journal as one that is classified into more than one macro-discipline.

Intersectoral research is defined as research that involves authors from non-academic sectors, such as government and industry (Tijssen, 2006). To investigate patterns of intersectoral co-authorship, we classified all authors into four societal sectors: academia (university and research institutes), government, industry, NGOs and other organizations. Classification was based on typical words in the name of the organization and, if available, website information, as organizations with the same kind of name may function differently in different countries. (For definitions of the organizational classes, see Appendix B.) Some organizations may have been assigned to the wrong class. However, such errors have no effect on aggregate patterns across large amounts of data.

3.2.1. Diversity measurement

To measure the degree of international, interdisciplinary and intersectoral collaboration in the development of UWS, we used a general framework for analyzing system diversity proposed by Stirling (2007). Specifically, we focus on two basic properties of diversity, namely variety and balance (Stirling, 1994).

Variety is the number of categories in a set. Balance measures the distribution of elements across categories. Balance is calculated using the Shannon-Wiener index. Given n possible categories in the set with proportions $p_1, p_2, \ldots, p_i, \ldots, p_n$, the Shannon-Wiener index, H', is defined as

$$H' = -\sum (p_i)(\ln p_i)$$

To interpret the result, we compare H' with the maximum of H', $H'_{\max}$, assuming all categories are equally distributed:

$$H'_{\max} = -\sum \left(\frac{1}{n}\right) \ln \frac{1}{n} = \ln n$$

The ratio $H'/H'_{\max}$, which ranges from 0 to 1, is the overall measurement for the balance across categories, where a high value indicates a high degree of diversity and a low value indicates low diversity.

4. Results

In this section we report the results of our statistical tests for answering the research questions.

4.1. Social interactions in the network of congress participants

We examined the behavior of participants in the IWA World Water Congress & Exhibition 2012. Participants visited different sessions, producing a session co-attendance network. We then constructed a session co-attendance network based on participation in the IWA World Water Congress & Exhibition 2012 (Fig. 1). The co-attendance network comprises 1581 participants, who attended between 1 and 24 congress sessions. Co-attendance shows that participants were likely to meet and may have communicated, not that they did meet and communicate. We identified five clusters or communities in the co-attendance network. These communities consist of participants who shared similar participation behavior and who more frequently attended sessions with other attendants within the same community than with attendants in other communities. Clusters in this network reveal the possible existence of communities of actors in the worldwide network of water professionals.

There were 198 congress sessions, each with a specific topic. The fields differ in age, community maturity, and the nature of knowledge. Based on the topics of the sessions attended by participants (Fig. 2), we found five communities: (1) a core UWS community, (2) a microbial ecology community, (3) a mixed community, (4) a biotechnology community, and (5) a less active UWS community.

The core UWS community (community 1) is significantly different in three ways (Table 2). First, it is far more international than the other four communities, involving participants from 74 countries. Second, it is the only community in which participants from science are not in the majority. Third, and related to the second observation, it is the community with the most even representation of participants from different sectors. Communities 2, 3 and 5 are dominated by academic participants. Community 4 is a mix of participants from academia and industry, interested in biotechnology. The results confirm the trends in internationalization and intersectoral collaboration called for in urban water management.

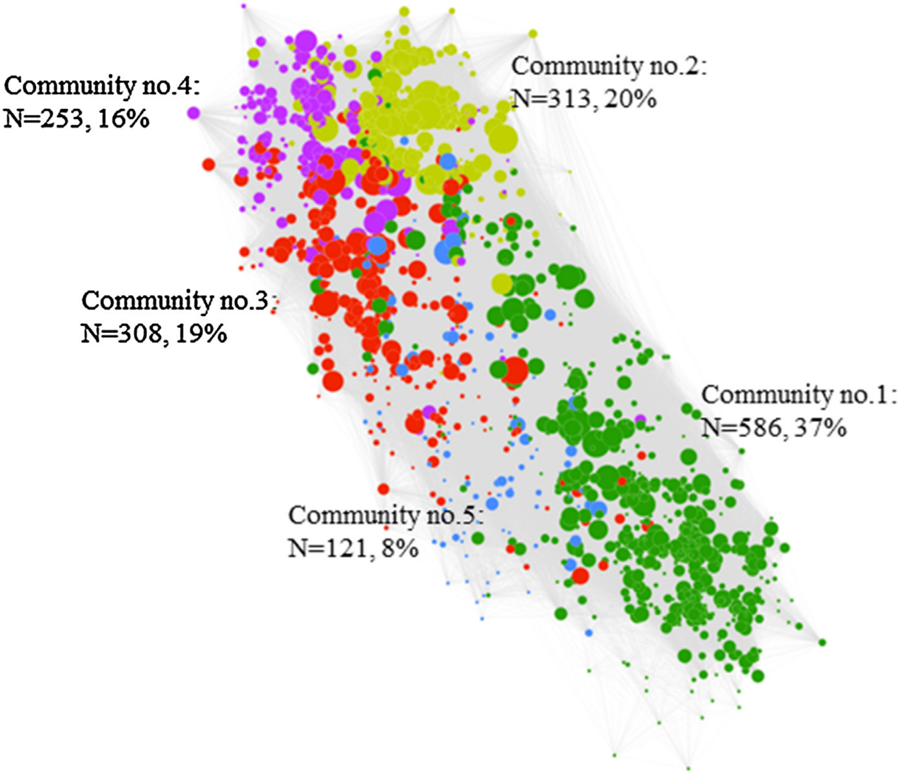

Fig. 1. The co-attendance network of congress participants in the IWA World Water Congress & Exhibition 2012 organized by the International Water Association (IWA); and detected five communities.

4.2. Growth

Before examining patterns of collaboration, we briefly describe the growth of scientific output in UWS. The number of scientific publications in UWS has grown dramatically since the 1990s (Fig. 3(a)). We have also examined the number of UWS publications as a percentage of all publications in the WoS published to find out if this development reflects the autonomous growth of all of science or is specific to UWS. Since 1990, UWS has increased from less than 0.01% of all publications to 0.15% in 2012 (Fig. 3(b)). This indicates that the high rate of growth is specific to UWS. We have conducted iterative Chow tests to test for the presence of a structural break in output growth. The results show

Table 2
The organizational properties of the five communities in the co-attendance network.

	Community 1 (*N* = 586, 37%)	Community 2 (*N* = 313, 20%)	Community 3 (*N* = 308, 19%)	Community 4 (*N* = 253, 16%)	Community 5 (*N* = 121, 8%)
Theme	'UWS'	'microbial ecology'	'mixed'	'bio-technology'	'UWS (less active)'
# of countries involved	74	42	41	33	25
Science	42%	78%	74%	57%	71%
Industry	20%	16%	13%	36%	5%
Government	22%	3%	7%	6%	17%
NGO	16%	2%	6%	2%	7%
Diversity (balance)	0.95	0.48	0.61	0.68	0.64

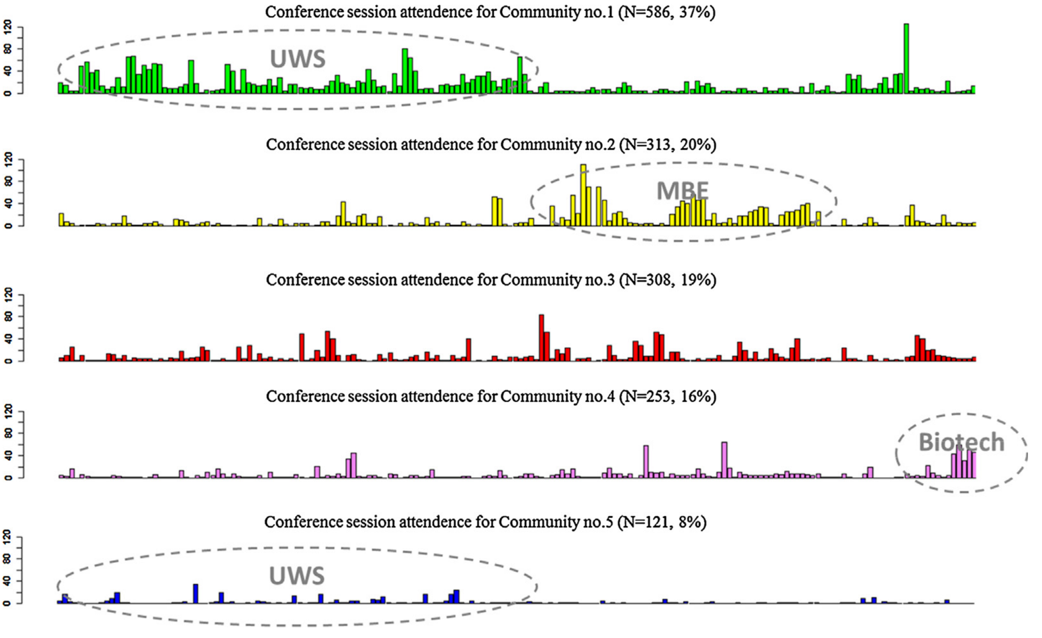

Fig. 2. Communities in the session co-attendance network of participants in the IWA World Water Congress & Exhibition 2012 organized by the International Water Association (IWA).

that the year 2004 was a turning point in the growth of UWS output. After 2004 the trend in output was significantly steeper than before.

4.3. *Intersectoral collaboration*

Are the intersectoral professional collaborations reflected in an increase in intersectoral collaboration in scientific knowledge production? If we look at the database of publications in UWS, we find

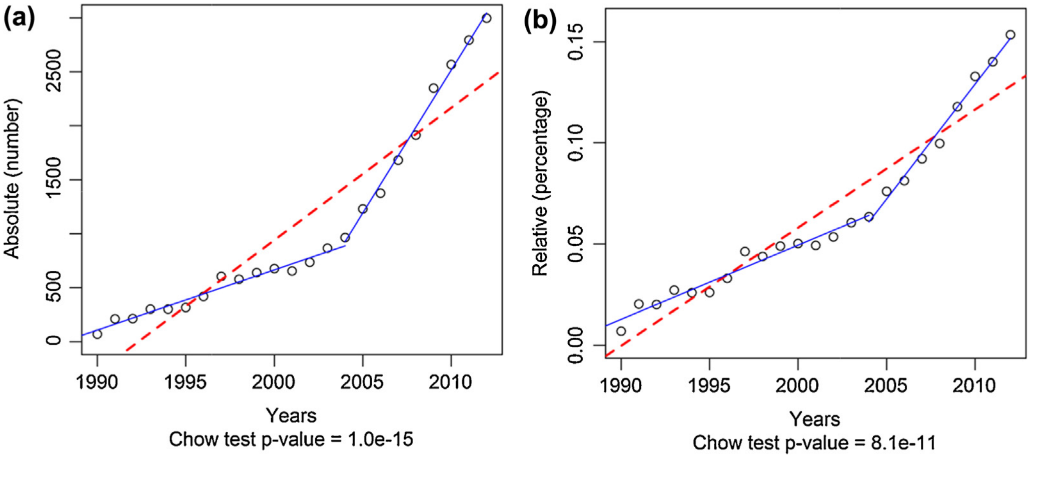

Fig. 3. The development of UWS output in absolute numbers (a) and relative to the total number of publications in the Web of Science (b) in 1990–2012. *Note*: The dashed line is the linear trend in UWS output across the entire period. The uninterrupted lines are the partial linear trends in output in 1990–2004 and 2004–2012.

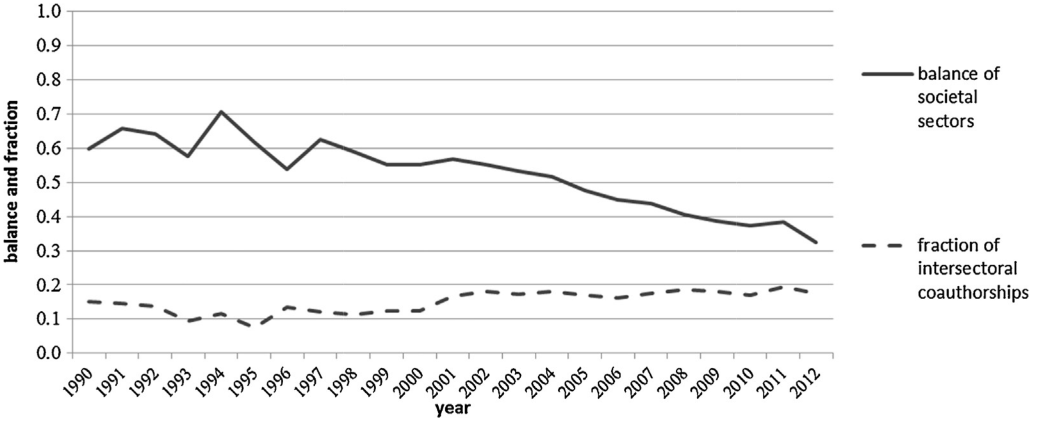

Fig. 4. Intersectoral collaboration in UWS. *Note*: Universities and research institutes are considered as part of the same sector (academia). Balance measures the distribution of UWS output across sectors.

that over the last two decades, the diversity (balance) of organization types has declined (Fig. 4). Contrary to expectations, the percentage share of universities and research institutes in the total number of scientific publications of UWS has increased, which means knowledge production as reported in publications in scientific journals is still primarily located at scientific institutions. On the other hand, the collaboration across the boundaries of science, government, industry, and NGOs has increased slightly. Fig. 4 shows that the fraction of intersectoral co-authorships has fluctuated during the 1990s and gradually moved upwards from around 10% to nearly 20% in the 2000s. The discrepancy between the sectoral diversity of the field and the co-authorship patterns implies that intersectoral collaboration is slowly increasing, but that universities and research institutes remain at the center of knowledge production.

We examined patterns of co-authorship in UWS output, distinguishing between single author papers and multiple author papers, and between multiple-author papers with one research address, and with multiple addresses, involving one or more sectors (Table 3). The results show that between 1991/95 and 2006/10, co-authorship between academia (universities and research institutes) and non-academia (government, firms, and NGOs) has increased for non-academia, whereas it has decreased for academia. Particularly, government and industry have become increasingly involved in collaborations with academic organizations. Within academia, the collaboration between universities and research institutes has also increased.

4.4. *Interdisciplinary collaboration*

Are collaborative scientific regimes increasingly interdisciplinary? The diversity of disciplines in UWS has slightly increased over time (Fig. 5). The fraction of articles published in an interdisciplinary journal has also slightly increased. This development may indicate that UWS increasingly integrates a broad range of knowledge from different disciplines related to social, political, managerial, infrastructural issues.

4.5. *International collaboration*

Are collaborative scientific regimes increasingly international? Fig. 6 shows that the number of countries involved in producing UWS output has increased as well as the fraction of publications produced in international collaboration. The network used to be dominated by the USA and a few European countries. Over time more countries have become involved and scientific output has become

Table 3
Patterns of co-authorship in UWS publications, 1991/95–2006/10.

Sector		Period	Papers (N1)	Single-authored or no collaboration	Collaboration			
					Papers (N2)	Within-sector	With academia	With non-academia
			N1	% of N1	% of N1	% of N2	% of N2	% of N2
Universities	Academia	1991–1995	410	62.7	37.3	54	12	34
		1996–2000	1786	55.9	44.1	48	21	31
		2001–2005	3806	44.2	55.8	46	22	32
		2006–2010	9659	37.8	62.2	50	23	27
Research institutes		1991–1995	100	57.0	43.0	16	44	40
		1996–2000	523	42.8	57.2	19	55	26
		2001–2005	1247	28.3	71.7	20	53	28
		2006–2010	3219	22.1	77.9	21	55	24
Government	Non-academia	1991–1995	105	51.4	48.6	24	55	22
		1996–2000	451	43.0	57.0	20	61	18
		2001–2005	923	24.1	75.9	17	67	16
		2006–2010	1828	13.3	86.7	16	70	14
Industry		1991–1995	158	57.6	42.4	30	55	15
		1996–2000	343	48.7	51.3	9	62	30
		2001–2005	612	23.7	76.3	12	65	23
		2006–2010	1262	13.5	86.5	12	69	18
NGOs		1991–1995	12	58.3	41.7	0	80	20
		1996–2000	122	29.5	70.5	9	69	22
		2001–2005	265	17.7	82.3	11	68	21
		2006–2010	601	9.7	90.3	11	70	19

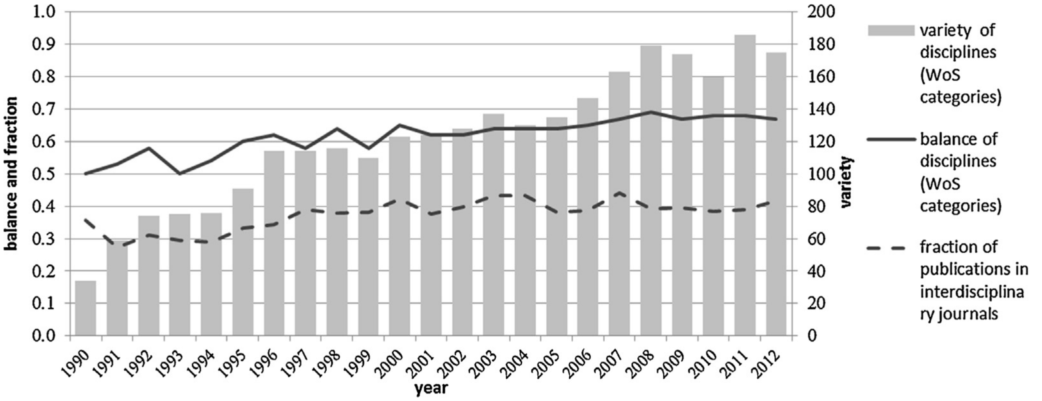

Fig. 5. Indicators of interdisciplinarity in UWS, 1990–2012. *Note*: Variety measures the number of WoS categories presented in UWS output. Balance measures the distribution of UWS output across WoS categories; higher values indicate higher diversity.

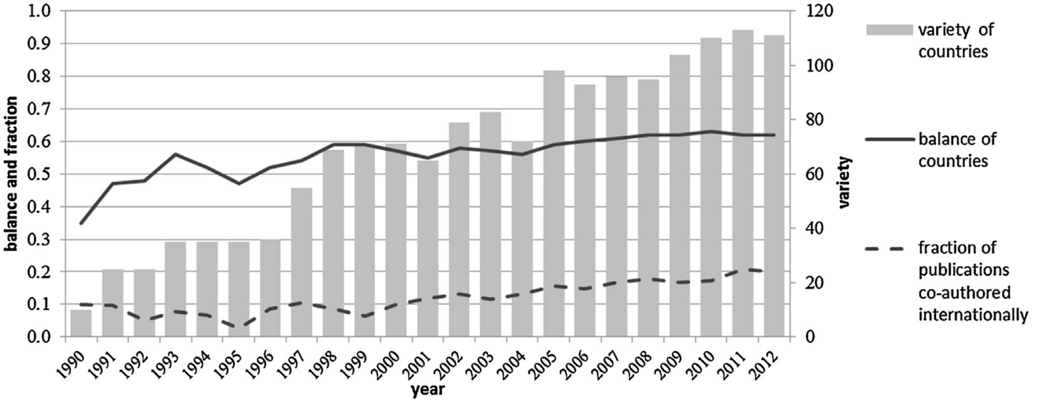

Fig. 6. International collaboration in UWS, 1990–2012. *Note*: Variety measures the number of countries presented in UWS output. Balance measures the distribution of UWS output across countries; higher values indicate higher diversity.

slightly more evenly distributed among countries. The percentage of publications produced in international collaboration is slowly increasing, especially in specializations involving applied chemistry, medicine and health care. The increase in internationally co-authored papers is gradual. The majority of publications is still produced within a national context.

5. Discussion

In this section, we interpret and integrate our findings to answer the two research questions.

Firstly, we have examined interactions in UWS from a social perspective, that of congress session co-attendance. The results of that analysis show that the core community of UWS professionals is significantly different from other communities of congress attendants, in the way that it is more international, has a much stronger representation from outside academia, and has the most balanced representation of participants from different sectors. The results appear to confirm the notion that UWS has changed from a relatively isolated technocratic water engineering field to a field focused on integral and participatory water management. The analysis shows a professional field with interdependent relationships between science, industry, government, and society.

The IWA World Water Congress & Exhibition is the world's only event encompassing all aspects of the water cycle, and it contains a variety of sessions with different sizes and orientations, such as purely academic, practitioner oriented sessions or a mixture. Our results may thus be, to some degree, generalizable to global water professional community. We have not looked into the longitudinal development of congress attendance, which means that we do not know if UWS has always been characterized by stronger cross-boundary interactions or if the intensity of interactions has increased over time. Also, co-attendance data show a potential for interactions and not of actual interactions nor the content of such interactions.

Secondly, in the scientific sphere of research publishing, the observation from the development of the scientific output of the field of UWS does not strongly support a similar trend in knowledge production toward more collaborative work.

The results show gradual changes in all areas:

- *Collaborative scientific regimes are slightly becoming intersectoral, however UWS remains an academic discipline.* Universities and research institutes dominate output. There has been a slight increase in collaboration between academic and non-academic organizations.
- *Collaborative scientific regimes are slightly becoming interdisciplinary*. UWS output has become slightly more interdisciplinary in the sense that more disciplines are involved and the relative importance of interdisciplinary journals has increased.
- *Collaborative scientific regimes are slightly becoming international.* International collaboration is growing gradually. The most remarkable change is that UWS is spreading to more and more countries around the world and that, where earlier UWS was dominated by the USA and a number of European countries, output is becoming more evenly distributed across the world. However, the majority of research is co-authored nationally.

The longitudinal analysis of scientific output suggests a limited gradual change in knowledge production on urban water management. One reason is that these results focus only on scientific output, which is potentially biased toward the reward system of science (Merton, 1957; Dasgupta and David, 1994). Academic members in the professional community on urban water management clearly have more incentives then other members to publish in academic journals. As such the analysis can only provide an indirect measure for international, interdisciplinary, and intersectoral ways of working (Wagner et al., 2011). Another reason is that despite more intersectoral professional interactions, scientists on urban water management have kept their own communication arena, in which scientific knowledge production per se is separated from other ways of professional communications. This reason does not negate the first one. On the contrary: it questions the initial assumptions that a transition in UWS will, or even has to affect, scientific knowledge production.

6. Conclusion

This paper assesses if there is a transition in social, cross-boundary interactions in the professional community and research publishing of the field of urban water science. We provided a bibliometric approach for the assessment of transitions that are in progress. We introduced indicators that enabled to assess the nature of the development of the transition from international, interdisciplinary and intersectoral perspectives. Using these indicators might support a better understanding of the actual character of transitions.

We find that there exist cross-boundary interactions in the professional community of UWS that are associated with a transition. The professional interactions in UWS are more international and intersectoral than in other areas of water science. In the analysis of scientific output metadata, we find no empirical evidence for the rise of new modes of knowledge production in UWS. On the contrary, there is even a growth in traditional publication output.

One explanation might be that scientists have taken the lead in developing the knowledge needed for a more adaptive urban water management and that they communicate this knowledge in separate interaction arenas. The scientific arena is based on traditional communication among peers through publications and journals, while the professional arena involves communication and interaction with a broader set of stakeholders. Scientific communities will probably continue using their own communication institutions and instruments. This implies that we need to improve our understanding of the inner workings of the professional arena, for example through an in-depth study of intermediary and network organizations such as IWA. By organizing congresses and events, IWA provides opportunities for diverse actors to interact, verify their ideas, and create a shared vision in discussion with others, thus enhancing the sustainability of the scientific field of urban water management and transition management.

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Appendix A.

The list used as searching terms to acquire data from WoS is:

(TS = sustainability OR TS = reuse OR TS = reclamation OR TS = "flood control" OR TS = "dual water systems" OR TS = "microbial source tracking" OR TS = conservation OR TS = "risk assessment" OR TS = "water supply" OR TS = "storm water" OR TS = "stormwater" OR TS = "water reuse" OR TS = sewer OR TS = drainage OR TS = runoff OR TS = "resource recovery" OR TS = "sustainable water" OR TS = "low-carbon water" OR TS = footprint OR TS = "nutrient recovery" OR TS = "water footprint" OR TS = "water scarcity" OR TS = drought OR TS = "green roofs" OR TS = "green infrastructures" OR TS = "water squares" OR TS = "adapt* strateg*" OR TS = "adapt* effective*" OR TS = "climate robust*" OR TS = "water security" OR TS = "climate change" OR TS = "multi-source water supply" OR TS = sanitation OR TS = "water self-sufficien*" OR TS = "sanitary sewer overflow" OR TS = "urban metabolism" OR TS = "pluvial urban flooding" OR TS = waste water OR TS = "waste water treatment plant" OR TS = "water exploitation index" OR TS = "ground water" OR TS = groundwater OR TS = bioretention OR TS = "infiltration trenche*" OR TS = "sand filter*" OR TS = "porous paving" OR TS = "pervious paving" OR TS = "sediment* basin*" OR TS = "constructed wetland*" OR TS = "swales buffer strips" OR TS = "pond* lake*" OR TS = "rainwater tank*" OR TS = "aquifer storage and recovery" OR TS = "urban water management") AND (TS = urban*).

Appendix B.

The widely accepted definitions for each type of organizations were collected and specified for our study (Table B.1).

Table B.1
The category and definition of organization types.

Societal sector	Definition	Example
University	Universities and educational institution, dedicated to the activities of teaching and learning, and the pursuit of research.	Universities, university hospitals, colleges (graduate) schools, and the institute of technology
Research institute	Publically funded research organizations endowed for doing research.	Research institutes, research centers, key lab, and science academy
Governmental organization	Organizations in the machinery of government responsible for the oversight and administration of specific functions, established by national government, state government, legislation or executive powers.	Government or state agency, ministry, city, and port authority
Industrial organization	Private enterprises consisting of an individual or a group of people that collaborate to achieve certain commercial goals.	Proprietorship, corporations, partnerships, consulting, and limited-liability companies
NGO	Non-governmental organizations, normally legally constituted, citizen-based, and not-for-profit associations, operated independently from any form of government (also often referred to as “civil society organization” or CSO).	Associations

Firstly, the classification process was done automatically by scripting based on the name of affiliations which could be found through the authors' addresses. For example, the affiliations with any of the following terms ‘university’ (English),‘universität’ (German), ‘université’ (French), ‘universidad’ (Spanish), ‘università’ (Italian), ‘universitet’ (Danish), or ‘universiteit’ (Dutch) were classified into ‘university’. Exceptions without a term consisting of university such as ‘instituto de Ingenieria’ or ‘institute of technology’ or the abbreviations universities were also detected and classified into the category of universities. Secondly, we manually identified those organizations which could not be classified automatically, for example, MIT (Massachusetts Institute of Technology), CAS (Chinese Academy of Sciences), and Sawag (Swiss Federal Institute of Aquatic Science and Technology). Finally, for the unfamiliar organizations and abbreviations, we researched the profile information through ‘LinkedIn’, the world's largest professional network. For example, Black & Veatch was classified into ‘industry’ based on its self-reported information as privately held construction company; CPRM (the company mineral resources research) was classified into ‘government’ as it is self-reported as government agency through ‘LinkedIn’. Research institutes of government agencies (such as the US Department of Agriculture's Agricultural Research Service) were classified as government.

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