

# Role of city collaboration networks in the acceleration and attenuation of integrated water management

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## Abstract

Inter-city collaboration has gained prominence as a strategy to share practical experience and accelerate the spread of novel sustainability practices. This study explores the potential of collaboration as a means to foster the uptake of integrated water management (IWM). IWM is an innovative approach to water management regarded as key to achieving urban water sustainability. The uptake of IWM has generally been slow due to organizational and institutional challenges. To explore the potential of collaboration to accelerate uptake, we analyze collaboration among 45 cities in Arizona, USA, relative to their IWM engagement and organizational capacity. We find that collaboration patterns reflect cities' interest in learning about innovative practices. However, there is a tendency to primarily collaborate with others who are in close geographic proximity. IWM practices and organizational capacities are secondary drivers of collaboration. Overall, our findings show opportunities while also urging realistic expectations.

*Keywords:* Arizona; Collaboration; Integrated water management; Learning; Network analysis; Sustainability

## Highlights

- Cities that are more knowledgeable and diverse in their IWM practices tend to collaborate more.
- Geographic proximity is the central criterion for the selection of collaboration partners; IWM practices and organizational capacities are secondary criteria.

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- To accelerate the adoption of IWM, cities may find it helpful to build relationships with farther afield partners while also using the power of local relationships.
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## Introduction

Inter-city collaboration is increasingly gaining prominence in sustainability action as an approach to further diffusion of sustainability practices (e.g., Ilgen *et al.*, 2019). Collaboration networks offer platforms for cities to learn about novel sustainability practices, access other cities' experiences with these practices, gain context-specific advice, form partnerships to codevelop sustainability projects, and pool resources (e.g., Ilgen *et al.*, 2019). This paper explores the potential of collaboration to foster the uptake of integrated water management (IWM), an innovative approach to urban water management regarded as key to achieving urban water sustainability.

IWM is an alternative water management paradigm that emphasizes a shift away from traditional, fragmented service delivery toward a holistic approach to water management wherein all forms of water (e.g., drinking water, stormwater, and wastewater) are managed in a coordinated fashion (Daigger *et al.*, 2019). Practices associated with IWM are numerous and diverse. They include, for example, green infrastructure, use of alternative water sources, decentralization of water services, fit-for-purpose thinking, stakeholder involvement, water-sensitive urban planning, use of water-smart technologies, and integration of supply- and demand-side management (Berger *et al.*, 2020).

Despite the documented success of IWM (e.g., Tortajada, 2006; Gordon, 2014), the uptake of IWM practices has generally been slow (Biswas, 2008; Brown & Farrelly, 2009; Daigger *et al.*, 2019). This is mainly attributed to institutional and organizational challenges including lack of knowledge, financial resources, and personnel (e.g., Biswas, 2004; Rahaman & Varis, 2005). This paper considers the potential of inter-city collaboration to help cities mitigate these challenges. Using data from Arizona, current patterns of inter-city collaboration are described and studied in terms of whether those patterns are conducive to foster the uptake of IWM.

To this end, the next sections discuss the potential of collaboration to accelerate the uptake of sustainability practices and outline key characteristics of IWM. We then formulate a set of hypotheses about collaboration, which are concurrently tested in the empirical part. The paper ends with a discussion of key findings and needs for future research.

## The potential of collaboration to influence the uptake of IWM

Inter-city collaboration is expected to enhance the diffusion of novel sustainability practices such as IWM in two main ways. First, it fosters policy learning. Cities share experiences on the implementation of practices and their effectiveness in addressing sustainability challenges (Ilgen *et al.*, 2019). This information supports them in crafting effective and feasible strategies and setting realistic expectations. Second, collaboration opens doors to enhance cities' capacities. Partnerships and common visions are conducive to sharing resources such as financial capital, personnel, knowledge, and collective implementation of projects (e.g., Ilgen *et al.*, 2019).

The suspected benefits of collaboration match the organizational and institutional challenges regarded as the root cause of slow diffusion of IWM (e.g., Biswas, 2004; Rahaman & Varis, 2005). Fragmented

responsibilities and resource constraints, including insufficient knowledge, financial resources, and personnel, are central obstacles to IWM implementation (Ivey *et al.*, 2004; Brown, 2008; Brown & Farrelly, 2009). Collaboration could help mitigate these challenges by offering platforms for cities to exchange experience, transfer knowledge, generate knowledge, coordinate initiatives, jointly implement projects, and share resources (e.g., Ilgen *et al.*, 2019). In this way, collaboration networks may accelerate the uptake of IWM strategies by cities.

As with most seemingly simple solutions, there are some caveats to this approach. The benefits of collaboration for learning and capacity enhancement depend on the underlying collaboration patterns. Put differently, the benefits depend on the selection of collaboration partners relative to their IWM practices and organizational capacities. No single network structure is a panacea for enhancing problem-solving around water sustainability; however, studies find that certain network characteristics are more conducive to learning and capacity enhancement compared to others (Henry & Vollan, 2014). For example, network segregation is found to inhibit learning (Yodanis, 2000; Barnes *et al.*, 2016). A network is segregated when collaboration mainly takes place among actors who are similar in terms of a criterion or set of criteria. Segregation across knowledge systems often implies that knowledge generated in one part of the network does not diffuse to other parts (Henry & Vollan, 2014). If collaboration among cities predominantly takes place among cities employing the same IWM practices, then insights generated about these practices stay within the communities of adopters. In this way, collaboration networks may attenuate the uptake of IWM strategies by other cities.

Actual network structures may or may not exhibit the characteristics found to foster learning and capacity building. In fact, studies often find that while integrated networks are more beneficial to learning, most real-world networks tend to be segregated (Henry & Vollan, 2014; Henry, 2017). Accordingly, to assess the potential of the collaborative approach, we need to first gain a better understanding of how cities actually collaborate relative to their IWM practices and organizational capacity. This will allow us to assess whether we can rely on current collaboration patterns to deliver improvements in IWM. This study contributes to such an understanding by examining how collaboration among cities in Arizona, USA, relates to their portfolios of IWM practices and organizational capacities. The next section outlines key characteristics of IWM before we then introduce our hypotheses on the link between collaboration and IWM.

## IWM strategies

Integrated Water Resource Management – also known as Sustainable Urban Water Management, Sustainable Water Resource Management, Integrated Urban Water Management, and One Water – is an umbrella term for a broad array of innovative water management approaches. These approaches share an emphasis on holistic ways to water management, or as Daigger *et al.* (2019, p. 2) put it: they are ‘based on the premise that all forms of water in urban areas (rainwater, groundwater, surface water, drinking water, used water, and fit-for-purpose reuse water) are linked and form a system that provides the most effective service when managed in an integrated fashion.’

There is no sharp transformation from non-IWM to IWM in cities. IWM practices are gradually introduced into an existing water management system. This happens step by step and takes different forms (Berger *et al.*, 2020). Introducing IWM often creates knock-on effects across the system. For example, recycling water for high-quality purposes requires advanced treatment, which, in turn, necessitates upgrading the treatment

facilities. As such, implementing IWM is less about adopting individual practices and more about systematically changing a system to conform with IWM goals.

Due to its broadness and its systemic component, IWM is best thought of in terms of portfolios of practices or strategies. Based on an analysis of water innovations in Arizona, [Berger et al. \(2020\)](#) differentiate three main IWM implementation strategies. [Table 1](#) provides an overview of these strategies. The first strategy focuses on upgrading the existing infrastructure. IWM implementation in this strategy is limited and mainly consists of using digital technology and enhanced coupling of groundwater and wastewater management. The second strategy focuses on using IWM practices for stormwater management. It applies decentralized solutions such as green infrastructure and systematic city design to divert, capture, and use rainwater. The third strategy employs IWM practices for water conservation. Consumers of water services are engaged in water management through adjusting landscaping practices, installing fixtures, and using alternative sources, among others. These strategies are not mutually exclusive. A city can, for example, upgrade existing infrastructures and simultaneously introduce IWM practices for stormwater management.

All three strategies involve elements of IWM but take different forms and vary in terms of the degree of implementation. The first strategy largely maintains the logic of the traditional centralized paradigm and the responsibility to provide water services rests with utilities. In contrast, the strategies employing IWM for stormwater management and for conservation contain considerable shifts in responsibilities, systems, and behaviors. The combination of the three strategies provides a tool to systematically study the link between collaboration and different approaches to IWM.

Table 1. IWM strategies based on [Berger et al. \(2020\)](#).

IWM strategy	Main characteristics	IWM practices
Upgrading the existing infrastructure (limited IWM implementation)	<ul style="list-style-type: none"> <li>Enhanced coupling of management domains, particularly the use of reclaimed water to enhance groundwater stocks</li> <li>Upgrading the existing infrastructure</li> <li>Largely maintaining a centralized form</li> <li>Utilities stay responsible for water management</li> </ul>	Groundwater management Wastewater management Digital technology Physical infrastructure Centralized solutions <sup>a</sup>
IWM for stormwater management	<ul style="list-style-type: none"> <li>Decentralized technology</li> <li>Use of alternative sources, particularly rainwater</li> <li>Co-production, that is, utilities and citizens share responsibilities</li> </ul>	Stormwater management Decentralized solutions Built environment and city design Green infrastructure Water conservation (general) Alternative water sources
IWM for conservation	<ul style="list-style-type: none"> <li>Empowering citizens</li> <li>Water conservation is a key element</li> <li>Citizens regarded as partners</li> <li>Citizens take active roles (e.g., behavioral change and technology uptake)</li> </ul>	Water supply Water conservation (use reduction) Water conservation (environmental) Stakeholder involvement Education Markets Regulation Small-scale technology Landscaping

<sup>a</sup>Centralization vs. decentralization is a popular dichotomy in the IWM literature. Centralization usually stands for the ‘old’ paradigm, while decentralized or hybrid approaches are associated with the ‘new paradigm.’ As such, centralization is an important indicator of limited IWM uptake.

## Hypotheses of collaboration and IWM

A reoccurring observation in network studies is a difference in the number of connections that actors have (Easley & Kleinberg, 2010; Barabasi, 2014). Certain actors, usually a small minority, have considerably more collaboration partners than others. This observation can be explained by means of actor ‘fitness’ (Bianconi & Barabási, 2001; Caldarelli et al., 2018). Fitness refers to the intrinsic properties of actors such as information, resources, or success, which make them more attractive collaboration partners (Caldarelli et al., 2018). Other actors aim to connect with fit – that is, informed, well-resourced, or successful – actors because they hope to benefit from these qualities (e.g., Dijkstra et al., 2013; Caldarelli et al., 2018). In the IWM context, a fit partner could be one with more diverse practices or more capacity.

The relationship between the number of collaborators and actor fitness is often bi-directional. As already discussed, fit actors have more collaboration partners because others seek to connect with them. This is referred to as the ‘fit-get-richer’ phenomenon. At the same time, larger numbers of connections lead to greater fitness. This is referred to as ‘rich-get-richer’ phenomena (e.g., Easley & Kleinberg, 2010). Collaboration can enhance fitness through increased exposure to ideas and information. For example, cities with highly diverse IWM portfolios may be attractive collaboration partners because of their broad experience. Concurrently, better connectedness may allow these cities to gain access to heterogeneous IWM ideas and approaches and thus diversify their portfolios. Based on these considerations, we can formulate the following hypotheses:

***IWM practices 1:*** Cities with more diverse strategies have more collaboration partners.

***Organizational capacity 1:*** Cities with more organizational capacity (e.g., knowledge, financial resources) have more collaboration partners.

Actors may also engage in collaboration to mitigate risk (e.g., Schoorman et al., 1981; Beckman et al., 2004). This is different from connecting with a fit actor. When connecting with a fit actor, actors attempt to benefit from others’ qualities. In contrast, collaborating to mitigate risk means joining forces to share or reduce risk (Beckman et al., 2004). Collaborating can reduce risk, for example, by sharing the cost of a new technology, providing information about risk mitigation, or providing political cover for risky decisions. For this purpose, collaboration partners do not have to be fit.

IWM is associated with a profound change in water management. That involves risk related to feasibility, efficacy, and social acceptance of practices, among others (Biswas, 2004). Thus, we would generally expect cities engaging in IWM to collaborate more as a way of reducing risk. Among cities implementing IWM, there may be a finer distinction. IWM practices differ in the amount of change they require in present practices. For example, integrating new digital technology into a planned treatment plant likely requires less change than converting a city from irrigation to xeriscaping.

Since collaboration can help cities mitigate risks associated with change, we expect cities engaging in IWM strategies characterized by more radical change to collaborate more. Considering the IWM typology presented in the previous section, we may expect cities employing IWM for stormwater management or water conservation to collaborate more than cities pursuing limited IWM implementation. Accordingly, we hypothesize:

***IWM practices 2:*** Cities implementing strategies associated with more radical change are more likely to collaborate.

Another common observation relates to the similarity of collaborators. Actors are disproportionately connected with others who are similar in terms of a specific criterion or sets of criteria (McPherson et al., 2001; Henry, 2017). As mentioned above, networks wherein ties are mainly linking similar actors are called segregated. While network segregation is an observed feature of many networks, two processes of network formation may lead to segregated networks (for a detailed discussion of structure vs. process, see Henry (2017)).

The first process is homophily. Homophily refers to the tendency of actors to connect with others who are similar. Actors may actively promote homophily. They choose similar partners or try to avoid partners who are different (McPherson et al., 2001; Henry, 2017). For example, cities may seek to collaborate with cities that are similar in their IWM practice because they perceive the respective knowledge will be more beneficial. Homophily may also result from structural properties such as shared venues or interests (McPherson et al., 2001; Henry, 2017). For example, city representatives implementing similar IWM practices may collaborate because they attend the same events or engage in the same projects.

The second process is social learning. Social learning emphasizes a change in actor behavior as a result of collaboration. Those who collaborate tend to adopt one another's behaviors through the sharing of information and experience. For example, a city may implement a certain IWM practice because a collaborator recommended it. Social learning only applies to mutable actor characteristics.

The processes of homophily and social learning inform the following hypotheses:

***IWM practices 3:*** Cities tend to collaborate with other cities who engage in the same IWM strategy.

***Organizational capacity 2:*** Cities tend to collaborate with other cities who are comparable in terms of their organizational capacity.

While segregation is often applied to a single characteristic or set of characteristics, it can be extended to combinations of characteristics. For example, cities may be more inclined to collaborate with others who have similar organizational capacity *and* use comparable IWM strategies.

Finally, we may assume that collaboration is influenced by geographic distance and population size. To account for these effects, we include respective control variables in our models.

## Methods

Data for this study consist of survey responses from representatives of city governments in Arizona, USA. The survey focused on water-related challenges, solutions, and collaborations. The initial sample of government representatives was constructed using the U.S. Census of Governments and consisted of public officials in local governments whose FY 2012 budget included expenditures on water services including management of supplies, wastewater, groundwater, floods, and watersheds. The sample was expanded by adding representatives of governments relevant to water management as identified by survey respondents, experts in the field, and through gray literature. For this study, the responses of 130 representatives of 45 city governments were used.

### *IWM implementation*

We measured IWM implementation using an open-ended survey question. Respondents were asked to describe up to five innovations ‘that your local government is particularly proud of.’ Innovations in this context refer to ‘programs, technologies, or processes that represent new ways to improve the environmental performance, resilience, or social equity of water systems.’

The reported innovations were used to identify the IWM strategies that cities employ. For this, we used the typology by Berger et al. (2020) discussed earlier. We first determined for every local government the IWM practices (column 3 in Table 1) that it employs. We counted a government as employing an IWM practice if at least one reported innovation represented the respective practice. This yielded a dataset showing each government and each of the three strategies the practices implemented. Next, we determined for every strategy the average number of practices that governments in our sample employ. This provides an anchor point to identify governments who are disproportionately invested in a strategy. We use the term ‘particularly engaged’ to refer to these governments. We determined for every government the strategies in which it is ‘particularly engaged.’ The resulting binary variables (i.e., ‘particularly engaged’ or ‘not particularly engaged’ in each of the three strategies) are our measures for IWM implementation.

This is a relative measure of IWM implementation. We measure a city’s implementation of IWM relative to its peers. This approach allows us to account for comparative aspects involved in partner selection. Actors tend to select partners based on their qualities *relative to* other potential collaboration partners. For example, a city interested in learning about IWM for stormwater management is likely to select among potential collaboration partners a city with more experience in this strategy (not just a city with any experience).

Diversity in IWM was measured by counting the number of IWM strategies in which a government was particularly engaged. A government could be engaged in none, one, two, or all three of the IWM strategies.

The similarity of IWM practices among cities was determined by means of the Hamming distance of the respective strategies. The Hamming distance equals the number of strategies in which the IWM profiles of two cities differ. For example, if city A employs IWM for stormwater management and city B employs IWM for stormwater management and conservation, then the Hamming distance between cities A and B is one, that is, their engagement differs in one approach.

### *Collaboration*

Data on collaboration were gathered using a graphical roster instrument. Survey respondents were asked to select on a map the cities in the state ‘that your local government cooperates with on water issues.’ The survey used a broad understanding of cooperation including a variety of activities.<sup>1</sup> It explicitly specified that cooperating refers to ‘both formal relationships (e.g., sharing infrastructure

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<sup>1</sup> The academic literature makes finer distinctions between collaboration and cooperation (e.g., Margerum, 2011). We do not expect practitioners to use this distinction. Therefore, we use these terms interchangeably, as is common in everyday language.

costs or jointly implementing programs) as well as informal relationships (e.g., interacting at meetings or sharing information or advice).’ The individual responses were aggregated to the city level. This yielded a network showing collaboration ties among the 45 cities in our sample. Figure 1 provides an overview of the cities and their collaborations. An undirected and unweighted graph was used for our analyses.

### *Organizational capacity*

Finally, we measured organizational capacity using a rating question. Respondents were asked to indicate their agreement with three statements describing organizational capacity. The statements were crafted to measure three important characteristics of capacity, including the knowledge of local water professionals, financial resources, and interest and support of local populations:

1. Water professionals in my community have a good understanding of what innovations are out there (knowledge).
2. My community has enough financial capacity to invest in water innovations (finances).
3. My community is interested in adopting innovative approaches for water management (interest in change).

Respondents rated these statements using a seven-point ordinal scale with 1 indicating ‘strongly disagree’ and 7 indicating ‘strongly agree.’ We aggregated individual responses to the city level by taking

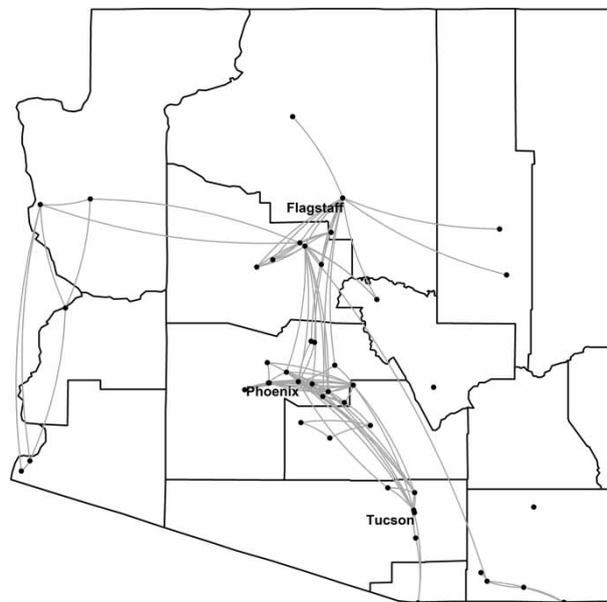


Fig. 1. Collaboration among cities in our sample.

the mean.<sup>2</sup> This approach, therefore, measures organizational capacity in terms of perceptions of respondents. While one may argue that perceptions may diverge from actual capacity, this approach offers two advantages that we consider outweighing this drawback. First, it allows us to quantify capacities that are difficult to assess using ‘objective’ measures such as knowledge and interest in change, allowing us to include capacity types that are often underrepresented. Second, perceptions are related to the situation on the ground and, therefore, provide a more accurate picture of available resources relative to the required capacity. For example, a certain amount of *per capita* financial resources may be sufficient or insufficient depending on the water situation of a city such as state of water infrastructure, amount of runoff, and available water resources. Purely ‘objective’ measures (e.g., per capita USD available in a year) do not pick up on this relative sufficiency and may therefore be misleading. This is particularly important because sharing of resources and resource-based collaboration is likely to depend on relative rather than absolute availability. The policy professionals responding to our survey have an intimate familiarity with local conditions and are therefore in the best position to judge these aspects of capacity.

We computed similarity matrices for each capacity item separately. The similarity of two cities was determined by means of the Euclidean distance of the respective capacity vectors. These data contain some missing values as not all city representatives answered all of the survey items. There was one missing answer for the knowledge item, two for the finance item, and four for the interest in change item. We employed different data imputation strategies including mean, median, and random resampling from the completed answers. The results were robust to these techniques. The models reported in this paper are based on imputation using medians.

Population counts for each city were retrieved from the 2017 population estimates by the [Arizona Office of Economic Opportunity \(2017\)](#). Geographic distances were calculated based on city coordinates.

### *Analytic approach*

Data were analyzed using social network analysis. Hypotheses are tested using exponential random graph (ERG) models. ERG models are used to explore ‘how the characteristics of the network members and larger social forces can explain or predict the observed patterns of relationships’ (Harris, 2014, p. 6). The dependent variable in ERG models is the presence and absence of collaboration ties (Robins *et al.*, 2007). The model predicts the likelihood of a tie between two actors. In this sense, network models are different from traditional statistical models. Most traditional statistical models focus on a characteristic or outcome variable associated with a single actor (e.g., the availability of financial resources is positively associated with the adoption of innovations). In contrast, the network models focus on relational characteristics between actors. They model tie formation (e.g., two actors who are similar in practice are more likely to form a tie).

The independent variables consist of attributes of the actors. These variables can be relational such as similarity in practice or distance between cities. They can also be actor characteristics such as the diversity of practices or the amount of knowledge. In addition, independent variables can consist in network configurations that the actors seek to create or avoid as they form ties (Robins *et al.*, 2007). For example,

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<sup>2</sup> To estimate the agreement of respondents within a city, we calculate the standard deviations. The standard deviations are on average 1.22 for knowledge, 1.19 for financial, and 0.89 for interest in change with distributions relatively narrow around the average. Thus, on average, respondents differ by approximately one standard deviation unit. This indicates general agreement, and we consider the data sufficient to examine general tendencies.

we often find that if an actor A collaborates with actors B and C, then it is likely that B and C also collaborate. This structure called dyad-wise shared partners can be added as an independent variable. This allows us to understand the effect of shared collaboration partners on establishing collaboration.

The parameters for the independent variables are estimated based on network simulations and expressed in a logistic regression-like statistical form (Robins *et al.*, 2007; Harris, 2014). The coefficients are estimated using a Markov Chain Monte Carlo (MCMC) parameter estimation algorithm (for a detailed discussion, see Harris (2014)). Put simply, network simulations are used to estimate coefficients for the different independent variables. These coefficients express the likelihood of forming a tie, for example, the likelihood of collaborating if two cities employ the same IWM strategies.

Here, we use the existence of collaboration ties as the dependent variable. Independent variables consist in the characteristics of the cities (e.g., diversity of IWM strategies) as well as relations between cities (e.g., geographic distance). Five ERG models were computed as follows. Models 1 and 2 represent main effects models. They examine the relationship between collaboration and diversity of IWM strategies (*IWM practices 1* hypothesis) and collaboration and type of IWM strategy (*IWM practices 2* hypothesis), respectively. Model 3 is a segregation model. It examines the relationship between collaboration and similarity in IWM engagement (*IWM practices 3* hypothesis). Model 4 is an interaction model. It focuses on how combinations of similarity in IWM practices and similarity in organization capacity relate to collaboration (*organizational capacity 1 and 2* hypotheses).

All models control for geographic distance and dyad-wise shared partner. Dyad-wise shared partners are known to improve model stability (Hunter, 2007). Models 1–3 also control for population size. Model 4 does not control for population size as doing so may obscure effects of organizational capacity.

The ERG models are fit using statnet (Handcock *et al.*, 2019). MCMC model diagnostics indicate that estimation algorithms are well mixed and the models converged (for a detailed discussion, see Harris (2014)). To assess the goodness of fit, we use the approach suggested by Saul & Filkov (2007). The approach draws from methods for the evaluation of classification models (Saul & Filkov, 2007; Cranmer & Desmarais, 2011). The basic idea is to compare overlap in ties between the observed network and a set of networks simulated based on the fitted model. We use 100 simulated networks to calculate the likelihood of a tie between any two actors. Next, we employ this information to compute a receiver operating characteristic (ROC) curve. The area under the ROC curve (AUC) ‘gives the integrated difference between the predictive success and predictive error of a classifier and represents a scalar-valued measure of model fit’ (Cranmer & Desmarais, 2011). Comparable to  $R^2$ , the higher AUC, the better the model fit (Cranmer & Desmarais, 2011). All models are comparable in terms of fit with an AUC between 0.87 and 0.89.

## Findings

The following sections present the findings of our analysis. We first provide a brief overview of key descriptive statistics of our data before turning to the ERG model results.

### *Descriptive statistics*

The network consists of 45 nodes (i.e., cities) and 112 collaboration ties. The average degree of a city – that is, the average number of collaborators – is  $\bar{x}_{\text{degree}} = 4.98$  ( $SD_{\text{degree}} = 4.1$ ;  $\text{median}_{\text{degree}} = 3$ ). The

degree distribution for this network is heavily right-skewed (skewness = 1.16) and platykurtic (kurtosis = 3.5), as is common for real-world social networks.

Organizational capacities were measured using a seven-point ordinal scale. Most city representatives report a relatively high interest in change ( $\bar{x}_{\text{interest in change}} = 5.7$ ;  $SD_{\text{interest in change}} = 0.93$ ) and fairly good knowledge of water innovations ( $\bar{x}_{\text{knowledge}} = 5.3$ ;  $SD_{\text{knowledge}} = 1.1$ ). The sufficiency of financial resources is clearly lower ( $\bar{x}_{\text{financial capacity}} = 3.7$ ;  $SD_{\text{financial capacity}} = 1.6$ ). However, there is a considerable spread in financial capacity.

### ERG model results

Table 2 shows the results of the ERG models. The coefficients in the table can be interpreted similarly to logistic regression coefficients. They indicate the change in log-odds to form a collaboration tie given a specific condition (see Levy (2016) for a detailed discussion).

Model 1 studies the relationship between diversity in IWM and collaboration. Cities not particularly engaged in any IWM strategy are the comparison group against which more diverse cities – that is, cities

Table 2. ERG models.

	Model 1 (main effects)	Model 2 (main effects)	Model 3 (homophily)	Model 4 (interaction effects)
Diversity of IWM (one area)	0.80* (0.01)			
Diversity of IWM (two areas)	1.18* (0.00)			
Diversity of IWM (three areas)	1.47* (0.00)			
Upgrading the existing infrastructure (limited IWM implementation)		0.27 (0.14)		
IWM for stormwater management		0.43* (0.03)		
IWM for conservation		0.66* (0.00)		
Similarity of IWM strategies (Hamming distance)			0.24 (0.08)	– 0.78* (0.02)
Knowledge				0.27* (0.02)
Knowledge distance (Euclidean distance)				– 0.49 (0.13)
Similarity of IWM strategies (as distance) × knowledge distance				0.31 (0.06)
Financial				– 0.02 (0.70)
Financial distance (Euclidean distance)				– 0.50* (0.03)
Similarity of IWM strategies (as distance) × financial distance				0.27* (0.03)
Interest in change				0.29* (0.03)
Interest in change distance (Euclidean distance)				– 0.57 (0.12)
Similarity of IWM strategies (as distance) × interest in change distance				0.22 (0.26)
Transitivity ( $\alpha = 0.87$ )	– 0.08 (0.20)	– 0.11 (0.11)	– 0.04 (0.57)	0.02 (0.76)
Population (in 10,000, log-transformed)	0.24 (0.00)	0.24* (0.00)	0.25* (0.00)	
Distance between cities (km)	– 0.02* (0.00)	– 0.02* (0.00)	– 0.02* (0.00)	– 0.02* (0.00)
Edges	– 5.87* (0.00)	– 5.27* (0.00)	– 5.02* (0.00)	– 3.93* (0.03)

\* $p < 0.05$ ; AIC model 1: 453.9; AIC model 2: 454.1; AIC model 3: 468.8; AIC model 4: 470.2.

engaging in one, two, or all three strategies – are compared. The coefficient for cities engaging in one, two, and all three IWM strategies is positive and increasing (0.8, 1.18, and 1.47, respectively) and highly significant ( $p \leq 0.01$ ). This provides support for our hypothesis (*IWM practices 1*) that cities with diverse portfolios – that is, one, two, or three strategies – tend to collaborate more compared to cities with less diverse portfolios – that is, no strategy. It is important to remember that our model does not allow for inferences of causality. Diverse cities might attract collaborators due to their ability of sharing experience with different techniques. Or, cities might be more diverse in their IWM practices because they collaborate more leading to greater exposure to ideas and learning. Also, it is important to note that the model controls for city size by means of population. Thus, the higher collaboration of diverse cities (in terms of IWM practices) is not simply an effect of larger city size.

Model 2 examines the relationship between the three IWM strategies – that is, upgrading the existing infrastructure, IWM for stormwater management, and IWM for conservation – and collaboration. More specifically, it tests for every strategy if cities particularly engaged in this strategy are more likely to collaborate, compared to cities not particularly engaged in this strategy. Based on our *IWM practices 2* hypothesis, we expect that cities implementing IWM for stormwater management and conservation are more likely to collaborate. The coefficients for IWM for stormwater management and conservation are positive (0.43 and 0.66, respectively) and significant ( $p < 0.05$ ). This provides support for our hypothesis.

Model 3 is a segregation model. It tests hypothesis *IWM practices 3*: cities engaging in similar IWM practices are more likely to collaborate. It is important to keep in mind that we measure similarities of cities in IWM practices using a distance measure (i.e., Hamming distance). Larger values of this distance measure indicate lower levels of similarities. Accordingly, a *negative* coefficient for the distance measure indicates that cities have a prevalence for *similar* collaboration partners – that is, cities prefer others who are close (small distance) in terms of the respective metric. The coefficient for the Hamming distance in IWM areas is positive (0.24). This would suggest that cities prefer to collaborate with others who employ different IWM strategies; however, the relationship is insignificant ( $p = 0.08$ ). Thus, the data do not support the hypothesis.

Model 4 examines the relationship between organizational capacity and collaboration. Organizational capacity is measured as knowledge, financial resources, and interest in change. Each of these characteristics is added as a node attribute and as distance (difference measure) between cities. The node attribute measures if cities that are high on any of these capacities are more likely to collaborate. The distances measure if cities that are similar in terms of the respective capacities (low distance) are more likely to collaborate. In addition, the model includes the IWM practice distance term already discussed above and interactions between this term and each of the organizational capacity distance terms. The interaction terms between distance in IWM practices and organizational capacity examine whether the combination of IWM practice *and* organizational capacity affects collaboration. For example, it allows us to examine if cities are more likely to collaborate with others who use the same practices *and* are similar in their knowledge.

The node attributes of knowledge and interest in change are positive (0.27 and 0.29, respectively) and significant ( $p < 0.05$ ). The node attribute of financial means is negative (−0.02) and non-significant. This indicates that cities characterized by higher levels of knowledge and interest in change are more likely to collaborate. Thus, we find conditional support for our first organizational capacity hypothesis. There is a relationship between organizational capacity and collaboration, *but* this relation depends on the type of capacity.

The organizational capacity distance term of finance is negative ( $-0.50$ ) and significant ( $p < 0.05$ ). Cities are more likely to collaborate with other cities that are similar in terms of their financial capacity. This can be an effect of homophily or capacity enhancement through collaboration. Cities may actively seek collaboration partners that are similar in terms of financial capacity (homophily), or they may enhance their financial capacity due to resource pooling. The model does not show a relationship between knowledge and interest in change. Again, we find limited support for our second organizational capacity hypothesis. There is a relationship between similarity in organizational capacity and collaboration, *but* this relation depends on the type of capacity.

The coefficient for distance in IWM practices in model 4 shows an interesting result. Recall that distance in IWM practice was insignificant if it is in a model by itself (model 3). In this model, however, the coefficient is negative ( $-0.78$ ) and significant ( $p < 0.05$ ). This indicates that similarity in IWM practices is not *per se* a determinant of tie formation. However, if we control for organizational capacity, it becomes a determinant. Put differently, among the cities that are similar in terms of organizational capacity, cities tend to collaborate with those who are also similar in IWM practices.

So far, our results indicate that similarity in financial capacity and IWM practice is positively associated with collaboration. This is in line with the concepts of homophily and the ideal of capacity enhancement. However, the interaction term hints at a more complex relationship. The interaction term for financial capacity and IWM practices is positive ( $0.27$ ) and significant ( $p < 0.05$ ). This indicates a nonlinear relation between collaboration, IWM practices, and financial capacity. To gain a better grasp of this relationship, we constructed a schematic graph showing the likelihood of collaboration ( $z$ -axis) given a certain amount of distance in financial capacity ( $x$ -axis) and IWM practice ( $y$ -axis) based on the ERG coefficients. The graph is displayed in Figure 2. The graph shows that cities are most likely to collaborate with others who are similar in terms of both financial capacity and IWM practice. They are also likely to collaborate with others who are dissimilar in both. However, they are less likely to collaborate with others who are similar in one but not the other. This finding is surprising at first glance. For example, one might assume that collaboration between cities with similar IWM practices and different financial capacity is attractive due to the higher capacity enhancement effects. There is a reasonable explanation for this observation though. The finding might be a manifestation of

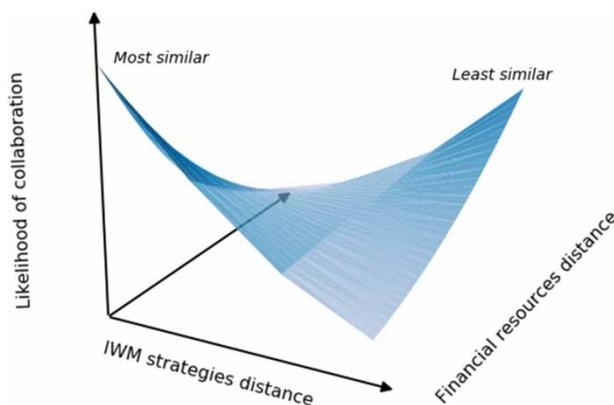


Fig. 2. Predicted likelihood of collaboration based on ERG model coefficients. Sampling space for financial resources was adjusted according to the range of values in data.

collaboration dynamics rather than of interest and benefit considerations. The divergence in financial resources may lead to imbalanced relations and undesirable power dynamics. Or implementation experience may not be transferable – for example, experience from a well-resourced city may not apply to cities with less resources, or experience with a particular IWM strategy may be of limited use to implement a different IWM strategy, even if financial resources are comparable. Our data do not allow to test such relations, and hence, at this stage, they are hunches to be tested in future studies.

Finally, we explore the effects of our control variables, geographic distance, and population size. We find a positive and significant relation between the size of a city and the likelihood to form ties. Larger cities are more likely to collaborate. Similarly, all models show a negative and significant relationship between geographic distance and tie formation. Cities are more likely to collaborate with cities in close geographic proximity. *Post hoc* analyses on the relative importance of different variables indicate that geographic proximity is a strong predictor. We achieve an AUC of 0.83 and an AIC of 491.6 by using only geographic distance as a predictor. We may thus suspect that cities tend to collaborate with their close neighbors with considerations of IWM practices and capacity being secondary criteria in partner selection.

## Conclusion

Inter-city collaboration networks are likely to be an essential pathway to enhancing the uptake of IWM in water policy through bottom-up processes of policy diffusion. During early stages of adoption, network-induced learning and capacity enhancement can gradually increase the number of cities employing IWM. Once a critical mass of local governments integrates these practices into their water management portfolio, the promotion of IWM through state- and federal-level institutions becomes less costly and risky and as a consequence their inclusion in higher-level policy more likely.

This study explored the link between collaboration and IWM using data from Arizona. Collaboration, as studied here, is an umbrella concept that is inclusive of many different sub-types of collaboration, ranging from formal to informal, low risk to high risk. It is certainly possible that different forms of collaboration matter differently for the potential uptake of IWM practices. However, our goal is to gain an initial overview of how cities collaborate relative to their IWM practices, examining nuances is left for future research.

Our findings show opportunities while also urging realistic expectations. These results highlight three key take-away messages.

First, cities tend to collaborate more with neighboring cities. IWM practices and organizational capacities are relevant but secondary criteria in partner selection. They may collaborate more with neighbors because of shared problems, similar context, and convenience, as well as more opportunities to meet at local events or develop relationships at superregional events based on common ground. The downside of preference for regional collaboration is that IWM expertise diffuses spatially which means that adoption may be slow. Spatial diffusion patterns are a common phenomenon for new technologies. The effect of geography tends to be strongest in early phases and decays over time (Comin *et al.*, 2012; see also spatial diffusion theory). This finding has direct practical implications. Cities interested in accelerating the adoption of IWM may find it helpful to build relationships with farther afield partners while simultaneously using the power of local relationships (Stoker *et al.*, 2018). Alternatively, it would be useful to bring national experience to local symposia to seed local discussions and help local knowledge jump to other regions.

Second, knowledge is a major driver and a potential result of collaboration. We find that cities that are more knowledgeable and diverse in their IWM strategies tend to collaborate more. This finding is consistent with the expectation of collaboration driving knowledgeability that is embedded in the idea of inter-city collaboration. If this causal link is true, then networking can indeed accelerate the spread of IWM practices. However, it may also be that predominantly the knowledgeable organizations collaborate with one another. This, in turn, could lead to an increasing gap between those who collaborate and obtain new insights on the one hand, and those with no or limited knowledge and networks on the other. Studying these mechanisms and the causal relations between collaboration, knowledge, and IWM adoption is an important topic for further research.

Finally, city governments seem to carefully consider benefits and collaboration dynamics. There are indications that cities may be avoiding collaboration that leads to imbalanced relations or that is associated with limited transferability of experience – for example, between cities that are interested in the same IWM strategy but have different amounts of resources available. This can create positive momentum for IWM, especially in early stages where adoption is slow and hard work. Collaboration among peers can spark new interest, create motivation, provide targeted experience, and keep progress going. However, it may reduce the capacity enhancement effect of collaboration, at least as it relates to financial resources. Cities with less resources may miss out on opportunities to enhance their IWM strategies that come from collaborating and potentially sharing resources with well-resourced cities. Generally, the link between IWM learning and collaboration dynamics warrants more research.

Overall this study indicates that collaboration has great potential to foster IWM adoption. However, it is important to keep realistic expectations. Collaboration will not lead to change overnight and should not be the only path that we pursue. Mandates and incentives from above or social movements and political activity from outside, for example, which encourage cities to change, will still be essential elements at play in local environmental policy change (Pivo *et al.*, 2020). While cities are connecting and learning, it is important that scholars keep doing their part by creating context- and praxis-sensitive concepts.

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## Data availability statement

Data cannot be made publicly available; readers should contact the corresponding author for details.

## References

Arizona Office of Economic Opportunity (2017). *2017 Population Estimates for Arizona's Counties, Incorporated Places and Unincorporated Balance of Counties*. Available at: <https://population.az.gov/sites/default/files/documents/files/pop-estimates2017-04pla.pdf> (Accessed November 20 2019).

- Barabasi, A. L. (2014). *Linked: How Everything Is Connected to Everything Else and What It Means for Business, Science, and Everyday Life*. Perseus Books Group, New York.
- Barnes, M. L., Lynham, J., Kalberg, K. & Leung, P. (2016). Social networks and environmental outcomes. *Proceedings of the National Academy of Sciences* 113(23), 6466–6471.
- Beckman, C. M., Haunschild, P. R. & Phillips, D. J. (2004). Friends or strangers? Firm-specific uncertainty, market uncertainty, and network partner selection. *Organization Science* 15(3), 259–275.
- Berger, L., Henry, A. D. & Pivo, G. (2020). Integrated water management recommendations in practice: coexistence of old and new ways in Arizona. *Water Policy* 22(4), 501–518.
- Bianconi, G. & Barabási, A. L. (2001). Competition and multiscaling in evolving networks. *Europhysics Letters* 54(4), 436.
- Biswas, A. K. (2004). Integrated water resources management: a reassessment – a water forum contribution. *Water International* 29(2), 248–256.
- Biswas, A. K. (2008). Integrated water resources management: is it working? *International Journal of Water Resources Development* 24(1), 5–22.
- Brown, R. R. (2008). Local institutional development and organizational change for advancing sustainable urban water futures. *Environmental Management* 41(2), 221–233.
- Brown, R. R. & Farrelly, M. A. (2009). Delivering sustainable urban water management: a review of the hurdles we face. *Water Science and Technology* 59(5), 839–846.
- Caldarelli, G., Capocci, A., Rios, P. & Munoz, M. A. (2018). Scale-free Networks Without Growth or Preferential Attachment: Good Get Richer. Available at: <https://arxiv.org/abs/cond-mat/0207366> (Accessed October 12 2020).
- Comin, D. A., Dmitriev, M. & Rossi-Hansberg, E. (2012). *The Spatial Diffusion of Technology*. National Bureau of Economic Research.
- Cranmer, S. J. & Desmarais, B. A. (2011). Inferential network analysis with exponential random graph models. *Political Analysis* 19(1), 66–86.
- Daigger, G. T., Sharvelle, S., Arabi, M. & Love, N. G. (2019). Progress and promise transitioning to the one water/resource recovery integrated urban water management systems. *Journal of Environmental Engineering* 145(10), 04019061.
- Dijkstra, J. K., Cillessen, A. H. & Borch, C. (2013). Popularity and adolescent friendship networks: selection and influence dynamics. *Developmental Psychology* 49(7), 1242.
- Easley, D. & Kleinberg, J. (2010). *Networks, Crowds, and Markets*. Cambridge University Press, Cambridge.
- Gordon, J. (2014). *On the Road to Independence: The Case of Water Management in Singapore*. Available at: [http://web.mit.edu/nature/projects\\_14/pdfs/2014-SingaporeWaterManagement-Gordon.pdf](http://web.mit.edu/nature/projects_14/pdfs/2014-SingaporeWaterManagement-Gordon.pdf) (Accessed October 12 2020).
- Handcock, M. S., Hunter, D. R., Butts, C. T., Goodreau, S. M., Krivitsky, P. N., Morri, M., Wang, L., Li, K., Bender-deMoll, S., Klumb, C., Bojanowski, M. & Bolker, B. (2019). *ergm: Fit, Simulate and Diagnose Exponential-Family Models for Networks*. The Statnet Project (<http://www.statnet.org>). R package version 3.9.4. Available at: <https://CRAN.R-project.org/package=ergm> (Accessed October 12 2020).
- Harris, J. K. (2014). *An Introduction to Exponential Random Graph Modeling*. Sage Publications, Los Angeles.
- Henry, A. D. & Vollan, B. (2014). Networks and the challenge of sustainable development. *Annual Review of Environment and Resources* 39, 583–610.
- Henry, A. D. (2017). Network segregation and policy learning. In *The Oxford Handbook of Political Networks* Victor, J. N., Montgomery, A. H. & Lubell, M. (eds). Oxford University Press, Oxford, UK, pp. 559–588.
- Hunter, D. R. (2007). Curved exponential family models for social networks. *Social Networks* 29(2), 216–230.
- Ilgén, S., Sengers, F. & Wardekker, A. (2019). City-to-city learning for urban resilience: the case of water squares in Rotterdam and Mexico City. *Water* 11(5), 983.
- Ivey, J. L., Smithers, J., De Loë, R. C. & Kreutzweiser, R. D. (2004). Community capacity for adaptation to climate-induced water shortages: linking institutional complexity and local actors. *Environmental Management* 33(1), 36–47.
- Levy, M. (2016). *ERGM Tutorial*. Available at: <https://www.r-bloggers.com/2016/05/ergm-tutorial/> (Accessed December 8 2020).
- Margerum, R. D. (2011). *Beyond Consensus: Improving Collaborative Planning and Management*. MIT Press, Cambridge.
- McPherson, M., Smith-Lovin, L. & Cook, J. M. (2001). Birds of a feather: homophily in social networks. *Annual Review of Sociology* 27(1), 415–444.
- Pivo, G., Henry, A. D. & Berger, L. (2020). Essential elements at play in local environmental policy change: a guide for the perplexed. *Environmental Science & Policy* 106, 240–249.

- Rahaman, M. M. & Varis, O. (2005). Integrated water resources management: evolution, prospects and future challenges. *Sustainability: Science, Practice and Policy* 1(1), 15–21.
- Robins, G., Pattison, P., Kalish, Y. & Lusher, D. (2007). An introduction to exponential random graph ( $p^*$ ) models for social networks. *Social Networks* 29(2), 173–191.
- Saul, Z. M. & Filkov, V. (2007). Exploring biological network structure using exponential random graph models. *Bioinformatics* 23(19), 2604–2611.
- Schoorman, F. D., Bazerman, M. H. & Atkin, R. S. (1981). Interlocking directorates: a strategy for reducing environmental uncertainty. *Academy of Management Review* 6(2), 243–251.
- Stoker, P., Pivo, G., Howe, C., Elmer, V., Stoicof, A., Kavkewitz, J. & Grigg, N. (2018). *Joining-up Urban Water Management with Urban Planning and Design*. The Water Research Foundation.
- Tortajada, C. (2006). Water management in Singapore. *Water Resources Development* 22(2), 227–240.
- Yodanis, C. L. (2000). Constructing gender and occupational segregation: a study of women and work in fishing communities. *Qualitative Sociology* 23(3), 267–290.

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