PROMETHEUS
2017, VOL. 35, NO. 3, 193–213
https://doi.org/10.1080/08109028.2018.1504867

RESEARCH PAPER

Sinking deltas: trapped in a dual lock-in of technology and institutions

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ABSTRACT

In delta areas, flood protection structures and large-scale land reclamation are preferential water management strategies to cultivate soft delta soils. Over the past decades, river embankments, upstream dams, land reclamation, and groundwater use have intensified, and increasingly contribute to subsidence. In addition, the influence of institutions implementing these strategies has strengthened as they have acquired technical skills, knowledge, and vast financial resources. Sinking deltas are therefore trapped in a dual lock-in as dominating technology and institutions act as constraints to moving into a more long-term sustainable direction. Nine factors for the lock-in are introduced and illustrated for delta regions in Asia, Europe, and the US. To gain a better understanding of what researchers and practitioners can do to address the dual lock-in, a practical case is presented of Gouda, a Dutch subsiding city in search of more sustainable strategies and institutions. The paper ends with three steps to change the configuration of a dual lock-in: (1) getting to know the lock-in; (2) temporarily bypassing it; and (3) constituting a new, more sustainable lock-in. These steps should be further investigated in action-oriented research programmes with local experts, and targeted to policy processes and human behaviour in the sinking deltas.

Sinking deltas and their threads

Sinking deltas in Asia, Europe, and the Americas (Syvitski *et al.*, 2009; Giosan *et al.*, 2014; Schiermeier, 2014; Schmidt, 2015a; Tessler *et al.*, 2015) are causing alarm bells to ring. Deltas are relatively flat plains located between rivers and coasts, hotspots of population growth and urbanisation for centuries (Seto, 2011). Their rich natural resources, freshwater availability, easy transport links, and fertile soil continue to attract people. Nowadays, 500 million people live below the 10 metre elevation mark in or near delta plains (Giosan *et al.*, 2014). Deltas are also flood-prone, both from the sea and

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from rivers because of their low elevation. Worryingly, many of these already low-lying areas are subsiding. Although deltas may subside naturally, human activities, such as groundwater extraction and drainage of embanked areas, exacerbate subsidence (Syvitski *et al.*, 2009; Galloway *et al.*, 2016). In addition, people in delta areas are faced with climate-induced sea level rise, upstream sediment capture by river dams, and coastal erosion downstream (Giosan *et al.*, 2014; Tessler *et al.*, 2015). These threats increase flood vulnerability (flood frequency, inundation depth, duration of floods), and hence, may result in major economic damage and even in loss of lives.

In many deltas, human-induced land subsidence occurs at a faster pace than climate-induced sea level rise. Specifically, the extraction of groundwater for domestic and industrial use causes subsidence of 6–100 mm/yr in many megacities, such as Jakarta, Bangkok, Ho Chi Minh City, and Shanghai (Erkens *et al.*, 2015). The drainage of soft soils causes subsidence of 5–50 mm/year in organic rich delta plains, such as the Venetian plain (Tosi *et al.*, 2016), the Dutch coastal zone (Erkens *et al.*, 2015, 2016), the San Joaquin delta (Drexler *et al.*, 2009), New Orleans (Erkens *et al.*, 2016; Jones *et al.*, 2016), and the Sumatra and Borneo coast (Hooijer *et al.*, 2012; Higgins, 2016). In these areas, subsidence exceeds both the current and predicted future sea level rise of 3–10 mm/year (Church *et al.*, 2011; Slangen *et al.*, 2012). In addition to increasing flood risks, human-induced subsidence causes significant economic losses in the form of structural damage and high maintenance costs for infrastructure. Land subsidence affects investment decisions for roads and transportation networks, hydraulic infrastructure, river embankments, sewage systems, buildings, and foundations. The total damage associated with subsidence worldwide is estimated to be billions of dollars annually (Erkens *et al.*, 2015).

Although the topic of sinking deltas has been put convincingly in the academic spotlight, we consider it highly unlikely that either subsidence or the resulting damage will reduce in the near future as subsiding deltas are trapped in a dual lock-in of technology and institutions. People, and the engineering technologies they have applied, are root causes of sinking deltas worldwide (Syvitski *et al.*, 2009; Giosan *et al.*, 2014; Schmidt, 2015a). To serve growing economies and populations, conventional water management strategies have increasingly been implemented (e.g. more dikes (Tobin, 1995; Temmerman *et al.*, 2013), dams (Zarfl *et al.*, 2015), groundwater pumping (Wada *et al.*, 2010; De Graaf *et al.*, 2015), land reclamation (Hooijer *et al.*, 2012; Erkens *et al.*, 2016)) that cause, exacerbate, or facilitate subsidence. The increasing implementation of these strategies has enlarged the power of those implementing it: in the US, an increase in dam and levee construction projects meant an increase in power of the US Army Corps of Engineers (Reisner, 1986; Tobin, 1995); in groundwater irrigation, rich farmers have a capacity to monopolise groundwater that poorer farmers do not (Aarnoudse, 2011); and key beneficiaries of more hydropower projects in China are the hydropower companies (Magee, 2006).

Enhancing understanding of the dual lock-in and seeking pathways for change are needed. Many deltas are on persistent, self-reinforcing paths of delta development with increasing areas of deltas sinking below sea level (Syvitski *et al.*, 2009; Renaud *et al.*, 2013; Giosan *et al.*, 2014). The aim of this paper is, therefore, twofold: first, to introduce the key factors of dual lock-in of sinking deltas and illustrate them with examples from around the world; and second, to share insights as to what policy-makers, researchers, and other actors can actively do to address their locked-in situations.

Theory

In the context of sinking deltas, we focus on the simultaneous lock-ins for institutions and technology as they jointly constrain behavioural change and collective action towards more sustainable delta technologies and institutions.

Increasing returns in technology and politics

The field of evolutionary economics offers explanations as to why mainstream technologies and institutions are favoured over newcomers. In his work on increasing returns and pathway dependencies, Arthur (1989) discusses how modern technologies display increasing returns to adoption: the more they are adopted, the more experience is gained with them, and the more they are improved. Adoption converges to one single technology, thus shutting out alternatives. So, because of increasing returns, one technology gets locked in, and other technologies become locked out (Arthur, 1994). A well-known lock-in example is the QWERTY keyboard (Arthur, 1989). Although superior alternatives, such as DVORAK exist, each computer is still fitted with a QWERTY keyboard as everybody is so used to it.

Arthur's (1989) increasing return theory focuses on technologies, and identifies why a certain technology is likely to expand because of the logic of increasing returns. These reasons include the large set-up costs of a technology, which create strong incentives for producers and users to stick with one option. By acquiring skills and knowledge in the operation of a complex technology, the technology becomes more efficient and effective, again making sticking to one technology attractive. The benefits for technology adoption may increase – for instance, reducing user costs – when a person adopts a technology that has already been adopted by others. From a producer's perspective, the increasing adoption of a technology reduces uncertainty, thus making users and producers confident about the quality of a specific technology (Arthur, 1989, 1994). In addition to these economic lock-in aspects, another technological characteristic is specifically embedded in civil engineering solutions. Large-scale structures, such as dikes and dams, have a certain 'hardness'; once they are constructed, they are not easily replaced or removed (Geels, 2004). In sum, a first set of factors can be derived, which emphasise technologically-related lock-in processes, such as learning about a technology, and the economies of scales and networks.

Based on the ground-breaking work of Arthur, Pierson (2000) brought the economic arguments of increasing returns to technologies to the world of politics and institutions. He discusses the main reasons for institutional pathway dependency, explaining why certain policy ideas, structures, and approaches become more institutionalised than others. Aspects identified include collective action, such as developing a new party or actor coalition. This involves high start-up costs, as it remains unclear whether other groups of people will join; hence, considerable resources (time, energy, finance) have to be spent before a collective group becomes self-financing. Similarly, new institutions and policies are costly to create, making existing institutional arrangements more attractive than hypothetical alternatives. Actors also tend to use their power and authority to generate changes in the rules of the game – formal institutions and public policies – to enhance their position. As a result, the linkages of policy goals, actions, and outcomes are unclear, which leads to the incorporation of confirming information and the filtering out of disconfirming information. Pierson's work thus offers a second set of lock-in factors that address institutional aspects to explain the inherent challenges of changing existing institutions.

Dual lock-in factors

To date, few studies have simultaneously addressed technical and institutional lock-ins; notable exceptions are studies in the field of low carbon technologies (Unruh, 2000; Foxon, 2002; Klitkou *et al.*, 2015). From the theory of technological and institutional path dependency, we have derived nine factors that contribute to the dual lock-in of technology and institutions in sinking deltas (Table 1).

Three properties of the dual lock-in emerge from these factors. The technological and institutional lock-in have co-evolved. This emphasises the strong interconnections between technological and institutional lock-ins as one particular technology is learnt and constructed. This knowledge is embodied in the skills, relations, and interests of prevailing institutions and their arrangements. A technological lock-in thus comes with an institutional lock-in in the context of water management strategies and sinking deltas. The connectivity is emphasised in the dual lock-in visual (see Figures 1–2, 4) that symbolises two magnets in which the north pole of one magnet (technological lock-in, red band) is solidly attached to the south pole of the other (institutional lock-in, grey band). Secondly, the dual lock-in is persistent as there are financial, technological, and social reasons to favour one technology or institution over another (Arthur, 1989; Pierson, 2000). Thirdly, the dual lock-in intensifies over time as institutions may use

Table 1. Dual lock-in of technology and institutions explained through nine interconnected factors.

Type of lock-in	Factor	Description
Technological	1. Scale economies	A technology has large set-up costs; production costs will decline as they can be spread over an increasing production time (Arthur, 1994).
	2. Learning effects	Specialised skills and knowledge have been acquired over time (Arthur, 1994).
	3. Adaptive expectation	Increasing adoption of a technology reduces uncertainty; people become increasingly confident about the quality and longevity of one specific technology (Arthur, 1994).
	4. Network economies	Benefits increase when a person adopts the same technology others already have (Arthur, 1994).
	5. Hardness	Once material structures are constructed, it becomes difficult to change them (Geels, 2004).
Institutional	6. Collective action	High start-up costs for taking collective action since it is uncertain if other institutions will do the same (Pierson, 2000).
	7. Institutional embedment	Existing institutional arrangements are more attractive than hypothetical alternatives as powerful organisations have invested in skills and relations with existing institutions (Pierson, 2000).
	8. Exercise of authority	When certain organisations are in a position to impose rules on others, these organisations may use their power to generate changes in institutions and policies to enhance their power (Pierson, 2000).
	9. Social interpretation	Organisations operate in a complex and opaque environment where links between actions and outcomes are loose and ambiguous. Confirming operation tends to be incorporated and disconfirming information is filtered out (Pierson, 2000).

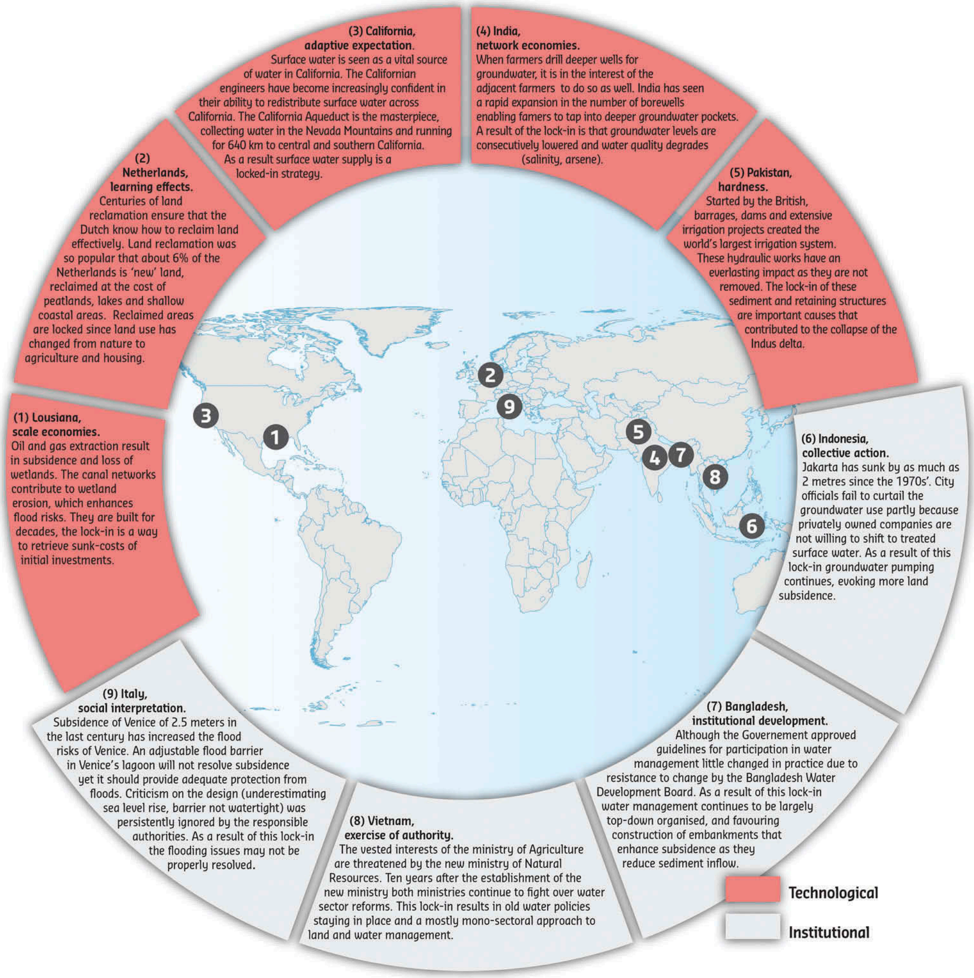

Figure 1. Examples of technological and institutional lock-in factors in subsiding areas worldwide.

Note: Figure 1 visualises the strong interlinkages of the technological and institutional lock-in as two magnets with the north pole of one magnet (technological lock-in, red band) clinging to the south pole of another magnet (institutional lock-in, grey band). The following references were used to prepare the text boxes (1)–(9): (1) Morton *et al.* (2006); (2) Hoeksema (2007); (3) Reisner (1986); (4) Fishman *et al.* (2011); (5) Pearce (2006) and Renaud *et al.* (2013); (6) Schmidt (2015a); (7) Warner (2003) and Schiermeier (2014); (8) Benedikter (2013) and Schmidt (2015b); (9) Sestini (1996) and Evelpidou and Pirazzoli (2015).

their power to strengthen their position (Pierson, 2000) and material structures, such as hydraulic works, that are difficult to remove (Geels, 2004; Van Staveren and Van Tatenhove, 2016), partly because they have large set-up costs (Arthur, 1989). The main outcome of a dual lock-in is that dominating technology and institutions are locked in, and that alternative technologies and institutional arrangements are usually locked out. In this paper, we use the dual lock-in factors as a framework to study socio-technical stability and change in subsiding areas, as well as the processes that shape and reinforce the prevailing technologies and institutions.

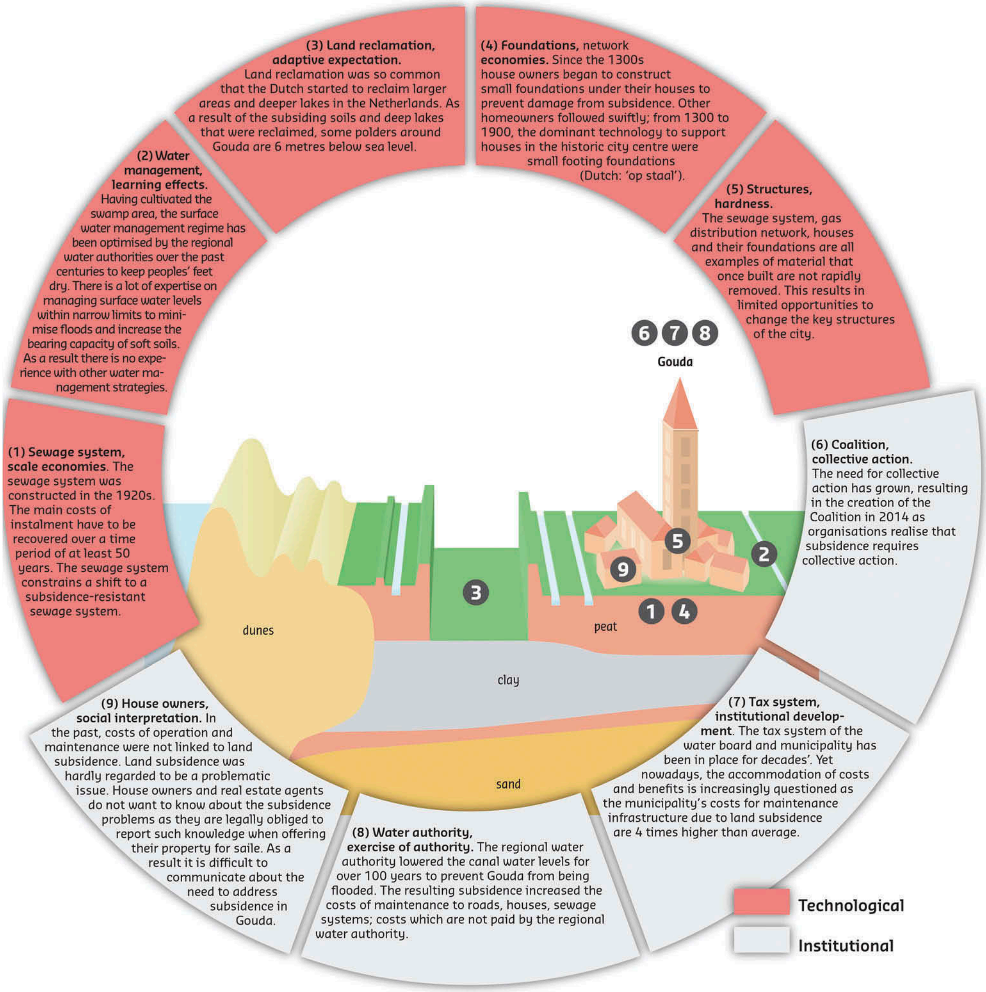

Figure 2. Technological and institutional lock-in factors explaining the persistence of the lock-in for Gouda.

Method

Research design

Our aim is twofold: illustrate the validity of the lock-in factors and share insights as to how to address the dual lock-in. This was achieved in four steps. First, we conducted a desk study to illustrate the nine factors for subsiding areas worldwide. Examples were included that reflect a variety among deltas, lock-in factors, and outcomes of the lock-in. Second, we selected two cases through a strategic sampling logic (Flyvbjerg, 2006), meaning that we did not randomly select the cases, but picked cases that would give a great amount of insight into the dual lock-in. The Vietnamese Mekong delta and the Dutch subsiding city of Gouda were selected because of their rich content regarding the dual lock-in. We knew that the cases were informative because of previous and ongoing research projects that provided us with in-depth knowledge on institutional and technological developments in both contexts (Minderhoud *et al.*, 2017; Seijger *et al.*, 2017). Narratives were thus created for the Mekong delta and Gouda on the basis of the different lock-in factors and their interplay.

Third, we prepared findings from our involvement in a strategy-seeking policy process in Gouda during 2014 and 2015. At that time, we had not yet identified the nine lock-in factors, but we did realise that subsidence in Gouda was a self-perpetuating process from which it was difficult to escape. Hence, we embedded several insights from working on transitions into our workshops; namely, prevailing mindsets can be challenged by illustrating alternative institutional configurations to those that are normally presented as dominant solutions (Ostrom, 1990); the interlinkage of technology and institutions should be reflected in problem analyses and strategies (Kemp *et al.*, 1998; Anadon *et al.*, 2016); and social learning across actors should focus not only on social challenges, but also on the potential of innovations (Geels and Schot, 2007; Raven *et al.*, 2010).

Fourth, we synthesised insights from the desk study, the Gouda case, and theoretical observations on addressing lock-ins into a three-step approach to shifting to a more sustainable dual lock-in. We recognise it will be ambitious and challenging to address the dual lock-in precisely because of the inherently strong, persistent forces at play that favour prevailing technologies and institutions. Nonetheless, opportunities may arise to work on transformational change, as shown by the Gouda case and as discussed in other transition pathway studies (Loorbach, 2010; Xia and Pahl-Wostl, 2012; Werbeloff *et al.*, 2016). When windows of opportunity open in subsiding areas, the three-step approach can be used as a starting point for problem analysis and formulation of strategy.

Methods in the Gouda strategy formulation process

The methods were applied over the course of four workshops in 2014 and 2015. Each workshop was attended by members of a coalition to develop ‘future-proof strategies’ for Gouda, consisting of governmental agencies (national, regional/local) and research institutes (see Table 2 for an overview). At the end of each workshop, participants filled in evaluation forms to evaluate the usefulness of the steps undertaken.

In the first two workshops, we worked with participants on an integrated problem analysis using group model-building techniques. Group model-building refers to the joint construction of a systemic causal loop diagram to understand messy, complex problems for key strategic decisions. Both the product (the causal loop diagram) and

Table 2. Overview of the participants in each of the four workshops (observers and moderators of the workshop are not included).

	Workshops I & II Group model-building	Workshops III & IV Perspectives for land subsidence
National government agencies	–	3
Regional and local governmental agencies	5	3
Independent chair of the coalition	1	1
Research institutes	2	2
Total	8	9

the learning process of developing the model with stakeholders are key outcomes of a group model-building process (Andersen *et al*., 2007). For Gouda, a group model was developed to analyse the problem of land subsidence in the city centre. During the two workshops, participants developed causal relations and compiled them into one qualitative causal loop diagram consisting of relations among 32 social and technical elements. The group model-building was facilitated by researchers from Radboud University Nijmegen.

In the third workshop, we created perspectives to explore a range of options for addressing land subsidence. The perspectives were created through scenario planning. Scenario planning methodology is used to come to strategic decisions for complex problems with high degrees of uncertainty in economic and social terms (Van Buuren and Popering-Verkerk, 2014; Beach and Clark, 2015). Various forms of developing and applying scenarios exist, depending on the goals, process design, and content (Van Notten, 2005). After consulting the participants on the key elements of the perspectives (scope, axes of matrix), we created perspectives for the year 2060 using a two-dimensional matrix. The axes of the matrix were allocation of responsibilities (public or private) and a strategic decision on land subsidence (halt or continue). This matrix resulted in four perspectives: public or private responsibility, and addressing causes or consequences of land subsidence. The perspectives provided four plausible future narratives on how Gouda might deal with the consequences of land subsidence by 2060 by discussing the dominating policy discourse for land subsidence and the associated roles, responsibilities, and resources of key actors. Participants individually scored the perspectives on various feasibility criteria (e.g. political, financial, technological) and the aggregated results were discussed collectively.

In addition, in the fourth workshop we created an overview of technical and institutional strategies for land subsidence to make the four perspectives more practical. Strategies were fitted to the different perspectives. The strategies covered the many dimensions of land subsidence: houses and their foundations, the water system, and legal and financial arrangements. To explore the implications of the strategies and perspectives, three strategies were discussed in more detail (as participants regarded them as applicable to all perspectives). These 'no-regret strategies' were discussed in the last workshop after which the participants assessed them through individual score-cards. The individual scores were added to a single overview sheet, followed by discussions about their feasibility, adaptability, and applicability to other regions. At the end of the final workshop, participants shared their key insights in a group discussion.

Results

Examples of deltas trapped in the double lock-in

Around the world, empirical illustrations of these nine factors are found (Table 1), constraining behavioural change and collective action towards more sustainable delta technologies and institutions in multiple ways (Figure 1). The examples of lock-ins range from oil and gas extraction in Louisiana to deeper groundwater drilling in India and persistent ignorance of criticism in Italy. The lock-in factors can also be applied to one particular subsiding area to explore their various facets and their interplay. What follows is a brief narrative of the dual lock-in in the Mekong delta and the city of Gouda in the Netherlands.

The Mekong delta in southern Vietnam is home to 17 million people and is subsiding at a rate of ~ 1–5 cm/year (Erban *et al.*, 2014). Most of the delta has an elevation within 2 metres of current sea levels; consequently, the delta is at risk of flooding and salinisation from sea level rise and subsidence. Major causes of subsidence are extensive groundwater pumping (Minderhoud *et al.*, 2017) and levee systems that prevent compensation by river sediments on subsiding embanked floodplains (Chapman *et al.*, 2016). In addition, sediment inflow into the delta was reduced by about 12% during the twentieth century (Syvitski *et al.*, 2009), and is expected to decrease further because of planned dams upstream (Kondolf *et al.*, 2014). The nine dual lock-in factors are ubiquitous:

- The production costs of hydropower dams have to be earned back in the coming decades (Factor 1).
- The network of river and canal dykes (180,000 km) (Chapman *et al.*, 2016) and >1 million groundwater wells (Erban *et al.*, 2014) will be difficult to change, let alone abandon (Factor 5).
- The extensive dyke system has been constructed over the past 40 years, during which time engineers from North Vietnam had to learn about the Mekong River's sediment flow (Benedikter, 2013) (Factor 2).
- Increasing confidence in dyke systems can be witnessed, since they were constructed in the coastal areas. In the coastal zone, they conflict with local livelihoods, as reflected by shrimp farmers who undermine the system of levees and tidal gates (Can *et al.*, 2010) (Factor 3).
- Rapid expansion of extraction wells and unsustainable mono-shrimp farms reveal how quickly farmers, for economic reasons, have adopted technologies from other farmers (Factor 4).
- Taking collective action for subsidence is challenging (Factor 8 in Figure 1).
- Research agencies are reluctant to share data, and hydraulic bureaucracy has formed a stronghold with the construction industry (Evers and Benedikter, 2009) (Factors 6 and 7).
- Despite research on the subsiding delta (Erban *et al.*, 2014; Schmidt, 2015b; Chapman *et al.*, 2016) and flagged in the Mekong Delta Plan (Royal HaskoningDHV *et al.*, 2013), subsidence receives limited attention in policy discussions (Factor 9).

In the Rhine delta in the Netherlands lies Gouda, a medium-sized city with about 70,000 inhabitants. The dual lock-in factors also pertain to this subsiding city (see Figure 2). The city initially developed on the elevated levees of a small river branch in a swampy peat area. Peatland cultivation began in the eleventh century to create arable land. These levees were narrow; newer expansions were built after medieval times in this former cultivated peatland. In all, the city and surrounding areas have subsided ~ 2–6 metres in the past 800 years (Erkens *et al.*, 2016). The subsidence is slow but irreversible, and results from groundwater level lowering over time and the loading of compressible peat deposits. Once subsidence commences, groundwater levels have to be lowered again, or the area has to be elevated with new soil, causing extra loading of the subsurface. These traditional adaptation strategies have been applied over the last 800 years by the regional water authority (i.e. lowering water levels) and Gouda citizens (i.e. elevating with new soil) and make subsidence in Gouda a self-perpetuating process. Not only have these strategies been optimised, but so are the institutions that implement them (see Figure 2). The result is, however, that Gouda continues to subside and that the municipality and its inhabitants are confronted with quadrupled maintenance costs (e.g. damaged roads and sewage pipes). In addition, some inhabitant's houses are flooded three times a year; for others, their houses are permanently damaged by differential subsidence.

The lock-in examples reveal several insights on the presence and functioning of a dual lock-in. First, the lock-in factors are found in different kinds of deltas, under different socio-economic conditions. They thus seem equally applicable to deltas with various socio-economic conditions and with different rates of subsidence (Erkens *et al.*, 2015; Higgins, 2016), or degrees to which deltas can grow quickly enough to keep up with sea level rise (Giosan *et al.*, 2014). Second, the dual lock-in concept is as applicable to a sinking delta, the Mekong delta, as it is to a sinking city like Gouda. This suggests that the dual lock-in factors are scale invariant. As a result, lock-in analyses should initially focus on one particular scale, after which they can be zoomed in or out to explore lock-ins at higher or lower scales. Third, the technological and institutional lock-ins interact and reinforce each other. Both in Gouda and in the Mekong delta, the application of a preferred technology came with specialised skills and knowledge – surface water levels in Gouda, levee system in the Mekong. This strengthened the influence of those in power: the Ministry of Agriculture in the Mekong, and the regional water authority in Gouda. As a result, analyses and strategies for subsidence should address both to avoid only one part of the lock-in being addressed.

A practical case: assisting Gouda in developing strategies for land subsidence

In this section, we report on our involvement in a strategy formulation process for the sinking city of Gouda. Decision-makers in the city of Gouda realise that conventional measures no longer suffice and new strategies are needed to address land subsidence. In 2014, the municipality forged a coalition with the aim of jointly developing future-proof strategies for central Gouda. The coalition consists mainly of governmental agencies and a range of research and knowledge institutes. What follows is a summary of the outcomes of the four steps that were undertaken with coalition participants.

Problem analysis

A group model was developed to analyse the problem of land subsidence in the city centre of Gouda. The constructed causal loop diagram (see Figure 3) reveals systemic relations between both technical elements (e.g. sewage system, groundwater levels, subsidence, foundations) and social elements (e.g. awareness, risk of damaged properties, liveability, political pressure, economic value of the city centre). Although participants were initially focusing on subsidence, they quickly realised that the inhabitants of Gouda do not care about land subsidence, but about the negative impact of land subsidence on the liveability in their city – increased pluvial floods, broken door entrances, and the smell of sewage spillovers.

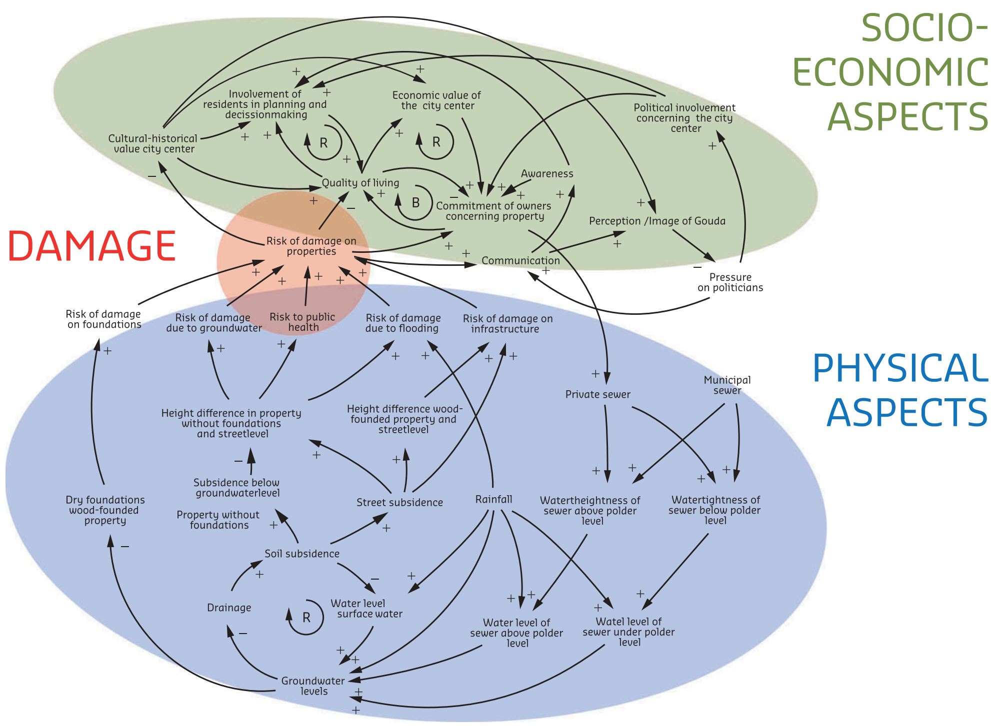

Figure 3. Causal loop diagram showing systemic relations between socio-economic and physical elements of subsidence in Gouda (with risk of damage to houses as main interlinking element).

Future perspectives

Four future perspectives for the year 2060 were created. The perspectives differed on both the allocation of responsibilities (public or private) and the strategic decisions to cope with land subsidence (halt or continue to subside). In the 'halt public' perspective, regional governmental organisations take the responsibility of addressing land subsidence in order to secure a liveable environment for Gouda. In the 'halt private' perspective, private organisations bear the responsibility of addressing land subsidence. In the 'subside public' perspective, the government does not see subsiding Gouda as a priority, and mainly responds to the severe consequences of subsidence. In the 'subside private' perspective, land subsidence is not perceived as a major issue by citizens. Discussing the different perspectives stimulated the participants to think about the prevailing 'subside public' institutional arrangement, and what may be needed to shift to other more preferred perspectives.

Strategies

Strategies covered the many dimensions of land subsidence, ranging from repairing foundations of buildings to water management adjustments or legal and financial arrangements. The strategies were fitted into the different perspectives, as is exemplified by managing the water system: in the 'halt public' perspective, the regional water authority keeps the water levels high in the canals; in the 'halt private' scenario, private companies and citizens take measures to store peaks of rain showers within the city; in the 'subside public' option, the regional water authority lowers the water levels to create storage for rain water infiltration, thereby provoking subsidence; and in the 'subside private' choice, inhabitants pump excess water out of their houses and basements. A prime insight that emerged while discussing the strategies with participants was that the prevailing 'subside public' perspective does not imply that regional governments can shut their eyes to land subsidence. Hard work is needed to address the consequences of land subsidence as Gouda continues to sink and major problems may even become aggravated, such as increased building subsidence, damage to roads, and required replacements of the sewage system. Discussions about the strategies yielded lessons on how and when to implement them.

Evaluation

In the final group discussion, participants agreed that the future perspectives and strategies were useful ways to explore different options to address land subsidence. Their understanding about the magnitude of the subsidence problem had improved, and they began to realise which kind of strategies could be adopted towards 2060. The strategies helped to make these perspectives more practical by specifying actions and responsibilities for public and private parties. Participants agreed that at this point it was too early to choose one preferred perspective or one set of strategies because of insufficient knowledge of the problem, of the strategies, and of the consequences for implementation.

The Gouda case contains several lessons for addressing the dual lock-in. First, opportunities may present themselves to address actively the dual lock-in as limits are increasingly experienced in technological and institutional matters. The traditional adaptation strategy of lowering water levels has resulted in quadrupled maintenance costs and concerns for liveability. By forming a coalition, opportunities arose for governmental and research agencies collectively to study and discuss the issue of land subsidence. Thus, despite the persistent nature of lock-ins, windows of opportunity may open. Second, if windows do open, the methods that were applied in Gouda – group model-building, scenario planning, strategy formulation – may stimulate thinking outside the lock-in box. By developing a causal loop diagram, participants realised that their problem perception was rather technocratic. The four perspectives and related strategies stimulated discussions on what might be needed in terms of technology and institutions to move out of the current lock-in. Third, it was easier for participants to discuss technical details of the strategies than to discuss shifting responsibilities or costs and benefits allocation between the municipality and the regional water authority. This re-emphasises the difficulty of discussing and addressing the institutional lock-in as it touches upon conventional power relations. Finally, the persistence of the dual lock-in becomes apparent. Although the dual lock-in problem was not resolved by going through the four steps in the Gouda policy process, at least a higher awareness was gained of the dual lock-in and potential ways to move out were identified and discussed.

Steps to change the configuration of the dual lock-in

As the Gouda case shows, opportunities may arise to work on transformational change in sinking deltas. Other examples are provided by water professionals who try to break prevailing mindsets through more accurate analyses of flood risks in a sinking delta

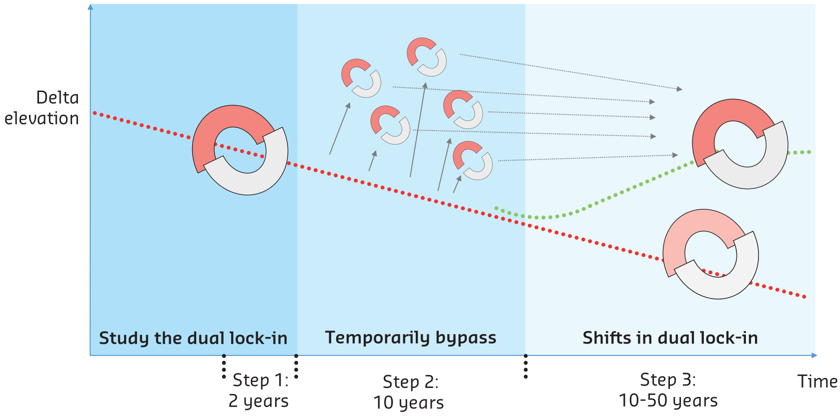

Figure 4. Constituting a new dual lock-in.

Note: The trend line reflects the insight that many of the world's largest deltas continue to sink, putting people and the environment at risk (Syvitski *et al*., 2009; Giosan *et al*., 2014; Tessler *et al*., 2015). Research in Step 1 should not only focus on the current situation, but also study historical developments that shape the current dual lock-in. The bypass efforts of Step 2 may or may not succeed. Therefore, two tentative pathways are shown in Step 3: one when shifts are achieved towards a more sustainable lock-in, and one in which the current lock-in prevails and sinking of the delta continues.*Source*: Adapted from various transition visualisations (e.g. Geels and Schot, 2007; Van Der Brugge and Rotmans, 2007; Sydow *et al*., 2009)

(Wesselink *et al*., 2007), and by scientists who challenge conventional wisdom and technologies for delta development by introducing innovations that mimic natural delta flows (Giosan *et al*., 2014). Our suggested steps are no manual for unlocking transformational changes in deltas; instead, they should be considered as a start and stimulus to undertake more efforts in analysing, experimenting, and managing the dual lock-in of sinking deltas. The three steps are visualised in Figure 4.

Step 1 – getting to know the lock-in through transdisciplinary research (1–2 years)

Subsidence is a complex problem, consisting of interconnected problems, major uncertainties on drivers, costs and rates, and diverging views on the problems and solutions (Syvitski *et al*., 2009; Giosan *et al*., 2014; Schmidt, 2015a). A solid problem analysis of, and social learning about, the dual lock-in is thus essential (Reed *et al*., 2010). Transdisciplinary research and involvement of local experts are needed as connections have to be made between engineering technology and institutions, surface and subsurface processes, and the management of the land–water–sediment system.

The Gouda case showed that a problem analysis could be undertaken through group model-building. The group model should focus not only on the systemic relations as such, but also on how the lock-in evolved. The following five questions touch upon key aspects in understanding the lock-in at play in a subsiding area; the indicative answers in-between brackets reflect the diverse configurations of subsiding delta areas:

- On what scale and in which environment does subsidence occur (local, sub-delta, delta, urban, rural, natural)?
- What are root causes and rates of subsidence (extraction of resources, lowering of shallow groundwater levels, loading)?

- Who is causing subsidence and who should act (industry, farmers, citizens, governmental agencies)?
- Who is affected, and in what way (damage to biophysical environment, infrastructure, buildings, increased floods, next generation)?
- How is the dual lock-in constituted, which factors are most influential in reinforcing the lock-in, and which factors offer openings for change (technological, institutional, both)?

Once an enhanced understanding on the dual lock-in has been obtained, crafting future perspectives – as was done in Gouda – with strategic decisions on how to cope with subsidence may raise awareness for possible alternatives outside the locked-in situation.

Step 2 – temporarily bypassing the dual lock-in through experiments in technology and institutions (~ 10 years)

When negative impacts of the dual lock-in increase and become visible (e.g. reoccurring floods in Jakarta (Schmidt, 2015a), saline intrusion caused by groundwater exploitation in the Mekong delta (Erban *et al.*, 2014), sinking wetlands in Louisiana (Morton *et al.*, 2006)), political pressure increases. Opportunities to bypass the lock-in emerge either gradually, as in Gouda, through the coalition and an extensive strategy-seeking process, or instantly, in the aftermath of such disasters as Katrina in New Orleans or Aila in Bangladesh. In line with political ambitions to minimise or even halt subsidence, new strategic priorities should be set for use of land, water, and sediment, and large-scale experiments with alternative technologies and related institutions should be conducted. In general, the more sustainable strategies are those that are positioned in a long-term perspective (Tessler *et al.*, 2015) and bring back natural dynamics into engineered deltas, such as nature-based flood defences (Temmerman *et al.*, 2013), reopening of closed-off floodplains to river (Chapman *et al.*, 2016) and tidal flows (Paul *et al.*, 2013), mimicking natural delta flows (Giosan *et al.*, 2014), recharging aquifers (Dillon *et al.*, 2010), and curbing groundwater exploitation in sinking cities (Erkens *et al.*, 2015).

When technology and institutions are interlinked in the pilots, they become the seedlings for breaking down the dual lock-in. New skills and knowledge are acquired in innovative strategies, and these strategies may generate new and additional benefits. These insights can be used to criticise overconfidence in, and limited benefits of, existing traditional strategies. The innovative strategies should be anchored in professional training and education. Linked to pilots on strategies, experiments with changes in institutional configurations should be held to break down the lock-in. This could range from new modes of collaboration (shown in Gouda's coalition) to experiments with financial policy instruments to stimulate behavioural change and technology adoption. These institutional bypasses could reduce start-up costs for collective action, provide a chance to reflect on common norms and ways of operation, and allow for novel skills, relations, and coalition-building among institutions (Sabbatier and Weible, 2007). During the bypass, decision-makers should emphasise novel understanding and potential long-term benefits, and that a balance has to be sought between those in power and those experimenting with new institutions (Schot and Geels, 2008).

Step 3 – constituting a new, more sustainable lock-in by making shifts in technology and institutions mainstream (10–50 years)

The shifts that have been explored in the lock-in factors during Step 2 should be pieced together and made mainstream in engineering, policy, planning, and governance in order to move towards a new, more sustainable lock-in (Geels and Schot, 2007). For instance, in education and professional training, new knowledge and skills are taught on connections in water–land–sediment systems, linkages between the surface and the subsurface, and the evolution of technology and institutions. The adoption of new technologies is anchored in new codes of practice. Legislation, financial mechanisms, and changes in responsibilities are anchored in an adapted institutional arrangement. Physical structures from the previous lock-in are gradually replaced with structures associated with the new, more sustainable lock-in. The new strategies and institutions are embedded in changed narratives on what a sustainable delta is, with more attention for natural dynamics, sediments, altered engineering technologies, and institutions.

Discussion

The aim of this paper is twofold: the first is to introduce and illustrate the key factors of a dual lock-in for sinking deltas, from which three properties characteristic of a dual lock-in appear (co-evolvement, persistence, intensification). The second is to explore what policy-makers, researchers, and other actors can actively do to address the lock-in. To date, social scientists have introduced the concepts of lock-ins, increasing returns, and path dependency (Arthur, 1989; Pierson, 2000), and institutional and technological lock-ins (Foxon, 2002). However, such a socio-technical understanding has been absent in the subsiding delta literature. Researchers who study subsidence have focused mostly on understanding the physical process of subsidence and its impact for deltas and societies (Syvitski *et al*., 2009; Giosan *et al*., 2014; Tessler *et al*., 2015). The dual lock-in concept thus offers a novel analytical framework to study the technological and institutional driving forces, their firm interconnections, and why increasing areas of deltas are sinking below sea level (Syvitski *et al*., 2009; Renaud *et al*., 2013; Giosan *et al*., 2014).

This paper shows the presence and functioning of a dual lock-in at city and delta scales in the Netherlands and Vietnam, respectively. The dual lock-in draws attention to conventional water management strategies (e.g. embankments, dams, land reclamation) and the accompanying institutional arrangements, both of which have been intensified and strengthened over time to accommodate growing economies and populations in deltaic areas. The strategies either cause, exacerbate, or facilitate subsidence, resulting in increased flood risks and high maintenance costs for infrastructure. The dual lock-in concept emphasises the stability of prevailing institutions and technologies, which largely disregard alternatives to address subsidence by focusing on social, economic, and technological reasons for sticking with the current strategies and institutions. The examples of the Mekong delta and Gouda reveal that the institutional and technological lock-ins are interlinked. The more one particular technology is learned and constructed (Factors 2, 3, and 5) through large-scale projects for land reclamation in Gouda or dike construction in the Mekong delta, the more the benefits for adopting the strategy increase (Factors 1, 5), while the increasing application of a particular strategy simultaneously reinforces prevailing institutional arrangements (Factor 7), power positions (Factor 8), and common norms and beliefs (Factor 9). This re-emphasises the value of understanding delta lock-ins from a socio-technical perspective and shows that one lock-in is not possible without the other.

The Gouda case deepened understanding of what policy-makers and researchers in other subsiding deltas can do to address the lock-in and seek ways out of it. Various methods were applied to stimulate social learning and draw people out of their locked-in mindset (Pahl-Wostl *et al.*, 2007). For instance, the causal loop diagram shifted the problem perception to the societal impacts of subsidence, and the future perspectives activity revealed four widely-differing approaches to cope with subsidence. The latter also made participants realise that they currently think and work within one perspective, but that alternatives do exist. What is also important is that the people of Gouda could work collaboratively on subsidence as there was strong political commitment from local and regional governments. Without political support and collaboration across key governmental organisations, it is very likely that land subsidence may only be partially addressed and thus not fully resolved. Meanwhile, our work in the Gouda case also highlighted the persistency of the lock-in. A preferred way out of the lock-in was not identified. However, awareness was raised on the current lock-in, and alternatives to move out were discussed, thereby enabling social learning about potential strategies and alternative institutional arrangements.

Despite the persistence of a lock-in, opportunities for change may come suddenly or gradually, and the opportunities may be driven by external or internal pressures (Greif and Laitin, 2004). We therefore presented a three-step approach to constitute a new dual lock-in. We recognise such an approach is ambitious, and perhaps a bit naïve, but we do regard it as a starting point for analysis and action when opportunities arise to work on strategies and institutions in subsiding areas. An important question remains whether good lock-ins exist, and if a sustainable lock-in, discussed under Step 3, is better than the current lock-in studied in Step 1 and bypassed in Step 2. To answer this question, we draw on Rittel and Webber (1973), who conclude that for complex, wicked problems, no optimal solution exists. Every implemented strategy leaves traces that cannot be removed. In consequence, lock-ins of the past are evident in subsiding deltas and there is little point judging whether they are good or bad. However, we can conclude at this point that subsidence is affecting more and more people, and that current lock-ins constrain the implementation of strategies that are positioned in a long-term perspective and bring back natural dynamics into engineered deltas. Changing the configuration of a dual lock-in thus seems sound, yet over time the limits of these new lock-ins will also become apparent as correcting for undesired consequences inherently poses another set of problems.

Conclusions and further research

The research community has convincingly put subsidence and its consequences for populations in deltas worldwide in the spotlight. In Asian megacities (Jakarta, Bangkok, Shanghai) and delta plains around the world (Italy, Netherlands, United States, Indonesia), subsidence surpasses sea level rise, thus further increasing flood risks and increasing maintenance costs for infrastructure in densely populated areas. We wrote this paper because of the shortage of the analytical concepts required to study and understand the social and technological factors that drive subsidence in the sinking deltas debate.

The dual lock-in provides a new, integrated understanding on the perseverant fate of the world's sinking deltas by uncovering the strong ties between institutions and technologies. The increasing application of conventional water management strategies – more dams, dikes, groundwater pumping, land reclamation – contributes to more subsidence and related risks for flooding and infrastructure, meanwhile enlarging the power of those implementing it. Through the nine lock-in factors, we offer explanations as to why these strategies and institutions are locked-in, and alternatives that might be more sustainable are shut out. The dual lock-in, and the strong interlinkages between the technological and institutional lock-in, can be determined through the lock-in factors.

We have provided empirical illustrations of the dual lock-in from around the world; further research could zoom in to particular areas to help understand how the lock-in evolved. The Gouda case showed, on the one hand, that a dual lock-in is very persistent, and on the other hand, that methods are needed which stimulate people to think beyond the current lock-in. Group model-building, future perspectives, and a mix between individual thinking and group discussions enabled learning across people from diverse government agencies and research institutes on the problem of subsidence and potential ways out.

Lastly, both the nine lock-in factors and the three steps to change the configuration of a dual lock-in may stimulate new research on subsiding delta areas and lock-ins (Step 1), possible bypasses (Step 2), and how to shape long-term shifts across people, decision-making, and technology (Step 3). Such research is preferably action-oriented or transdisciplinary, and covers both strategies and institutions for land subsidence, while feeding into policy processes undertaken in close collaboration with key stakeholders.

Acknowledgements

We are grateful to the participants in the Gouda case for their contributions in the workshops, and to the researchers of Radboud University Nijmegen for creating the causal loop diagram. We thank the municipality of Gouda for their support and commitment. In addition, we would like to thank two reviewers and the general editor of *Prometheus* for sharing their critical and valuable feedback. This allowed us to improve the paper's content and structure substantially. This research was part of the adaptive delta planning research theme funded by Deltares; the urbanising deltas project (W 07.69.106) of the world programme of the Netherlands Organisation for Scientific Research (NWO) Project Number W 07.69.106; and research programme BE SAFE financed primarily by NWO.

Disclosure statement

No potential conflict of interest was reported by the authors.

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