Institutional Adaptation to Environmental Change

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Abstract

In this paper we show that states form to overcome the adverse effects of environmental change. In a panel dataset of settlement, state formation, and public good provision in southern Iraq between 5000BCE and today, we estimate the effect of a series of river shifts. We hypothesize that a river shift creates a collective action problem in communally organizing irrigation, and creates demand for a state. We show four main results. First, a river shift negatively affects settlement density, and therefore incentivizes canal irrigation. Second, a river shift leads to state formation, centralization of existing states, and the construction of administrative buildings. Third, these states raise taxes, and build canals to replace river irrigation. Finally, where canals are built, river shifts no longer negatively affect settlement. Our results support a social contract theory of state formation: citizens faced with a collective action problem exchange resources and autonomy for public good provision.

Keywords: Environmental Change, States, Collective Action, Iraq. **JEL classification**: O10, O13, H70, Q5.

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1 Introduction

How do societies adapt to environmental change? Existing studies of successful adaptation have focused on short run adaptation to weather or temperature shocks (Barreca et al., 2016). We know much less about successful *long-run* strategies. This is particularly important since some factors, like institutions, may only adjust to environmental change over longer spans of time.

In this paper, we study state formation as an institutional adaptation to environmental change. We test the hypothesis that when the negative effects of environmental change could be offset by public good provision, states may form to address this 'demand' (Wittfogel, 1976; Algaze, 2009). The demand for a state is in turn driven by a standard collective action problem, which prevents private provision of public goods (Samuelson, 1954; Stavins, 2011). This demand side theory of state formation complements theories that emphasize coercion and top-down 'supply side' state formation (De La Sierra, 2018; Mayshar et al., 2018).

The setting of this paper is southern Iraq. Between 5000BCE and today Iraq's main rivers, the Euphrates and the Tigris, moved into their current course in a series of sudden shifts.[1] We estimate the effect of these river shifts on settlement, state formation, and public good provision in a new archeological panel dataset. Figure 2 maps our study area, and Figure 3 gives an example of a river shift.

Because in our study area farming relies on irrigating the otherwise arid desert, farmers can no longer be economically productive when a river shifts away. In response, they can either move to the new course of the river, or stay. When they stay, they can only farm if the land is irrigated by canals (Adams, 1981). While locally canals can be built and maintained communally, larger groups of farmers face a standard collective action problem resulting in underprovision and overuse of public resources. Farmers may therefore be willing to be taxed, and to enter into a social contract with a state that provides canal irrigation (Hobbes, 1651).[2]

In this setting, a river shift shocks economic production, the demand for public goods, and the incentives to form states to provide these public goods. We therefore expect a river shift to: first, negatively

[1]Because river shifts result from a surge in water volume brought on by extreme upriver rainfall in Turkey and Syria, they happen in a matter of weeks.

[2]We provide extensive historical evidence on taxation, public finance and the existence of a social contract for our study period. The impact of rivers on Iraqi society has been studied extensively by historians and archaeologists. For example, Robert Adams (1981, p. 1) writes: "The formative processes leading to the world's first urban civilization cannot be understood except as a creative adaptation to the priceless resource of Euphrates water."

affect economic activity through reduced irrigation. Second, lead to state formation. Third, lead, through the formation of states, to the construction of canals that irrigate the areas affected by the river shift. We furthermore expect these effects to be more pronounced where collective action 'pressure', the difficulty with which irrigation could be organized communally, is higher.

To test these predictions, we construct 5x5 kilometer grid cell panel covering southern Iraq. For each grid cell, we gather outcome data for 31 distinct archeological periods.[3] We also record the location of rivers at the beginning of each period. We combine these data in a dynamic panel difference-in-differences design, in which we compare grid cells directly next to rivers that shift, to grid cells whose nearest river stays in its bed, before and after a river shift. We express all treatment effects relative to the last pre-treatment period.

To establish that a river shift has an effect on economic activity, we collect archeological data on settlement and measure the number of settlements in a grid cell in each period. We find that grid cells experiencing a river shift see a reduction in settlement equal to about one-third of its mean. We argue that this effect works through reduced irrigation, and we support this idea by showing that the negative effect of a river shift is concentrated where farmers cannot rely on rainfall to substitute river irrigation. These results show that river shifts affect development in our setting, and therefore create incentives to adapt.

To study state formation as a strategy for adapting to environmental change, we compile a new dataset covering cities, administrative buildings, and states. We record whether a grid cell was part of a state as an extensive margin measure of state formation, and the number of administrative buildings in the nearest city to a grid cell, or in the capital of the state the grid cell is part of, as intensive margin measures. We also study where states locate their capital city.

Because we want to study the *process* of state formation we break up our panel along its time-series dimension and treat individual river shifts as separate experiments. We start by studying the formation of city states from scattered settlements. The first city states emerge around 3000BCE. We observe a river shift around 2900BCE, and we ask whether new city states are more likely to be formed, or existing city states are more likely to expand where a river shift increases the incentives for state formation. We find that a river shift leads to a 50% increase in the probability of a grid cell being part of a city state. We also

[3]These periods are classified by archeologists based on changes in styles of cultural artifacts, such as pottery. On average, a period is about 225 years long. Our main results are robust to using equal length 'synthetic' periods.

find that the number of buildings dedicated to government administration in the city nearest to a grid cell increases by a third, and existing government buildings in these cities are enlarged by about a third of their floor area. We then study the consolidation of these city states into a centralized state. The first successful consolidation of city states that coincided with a river shift happened around 1800BCE.[4] We study the location of the capital of the new centralized state relative to the locations of the capital of the scattered city states, to understand whether the administrative center of the new state moves to where the demand for public goods increased. Using distance to the capital city of the newly formed state as the dependent variable, we find that the new capital locates about 25% (or about 15 kilometers) closer to treated cells, relative to where the city states capitals had been. We find that administrative buildings are constructed and enlarged, but now in the new capital city and no longer in the former city state capitals. Our last experiment is a placebo in which a river shift coincided with an external invasion. In this placebo, no state could be formed due to the presence of a foreign army. We find no effect of a river shift on state formation.

From their administrative buildings, these states organized tax collection and public good provision. We hypothesize that public provision motivated Iraqis to pay taxes to the state rather than moving to the new course of the shifted river. To test this part of our hypothesis, we reconstruct the full network of irrigation canals between 5000BCE and today from archeological and satellite records. We find that a river shift is associated with a 30 to 65 percent increase in the probability that a grid cell is irrigated by a canal. These canals, by providing water to grid cells that were previously irrigated by rivers, allowed the population to farm where it had before. In our placebo period, the river shift has no effect on canal construction.

We close our argument by showing that in our city states and centralized state experiments, the negative effects of environmental change are offset. We restrict our sample to these periods before and after the relevant river shifts and re-estimate the effect of a river shift on settlement. We find zero effects of a river shift in both experiments. In our placebo experiment, we find a strong negative effect. Our earlier panel-wide finding that river shifts negatively affect settlement is driven by stateless periods, such as our placebo.

To establish a causal interpretation of these results we pursue three strategies. First, our empirical strategy allows us to directly test the parallel trends assumption by estimating treatment effects in periods before treatment occurred. If the parallel trends assumption would be violated, we would expect grid

[4] This attempt was undertaken by Hammurabi. Previously successful attempts were undertaken by Sargon of Akkad, and the URIII dynasty. This state fell apart about two hundred years before the river shift we study here.

cells that will be treated to look different before treatment, relative to the last pre-treatment period. We find parallel pre-trends throughout. Second, we show that river shifts are uncorrelated with lagged settlement and public good provision. If, for instance, human activity could alter the flow of rivers, we may expect river shifts to be more likely where economic activity is concentrated. Finally, our setting argues against alternative 'supply' explanations of state formation. Since a river shift reduces economic activity and therefore the tax base, we expect states maximizing extraction to form elsewhere. Similarly, individuals can always move to the new course of the river, further reducing the scope for coercive extraction.[5]

Taken together, these results provide support for the hypothesis of this paper: in response to a sudden change in the environment, states form, these states provide public goods, and these public goods offset the negative effects of environmental change.

The demand for public good provision, and the incentives for state formation it creates, have their origins in the collective action nature of collective organization of canal irrigation. In the remainder of our paper, we measure collective action directly, and ask whether more canals are built where it is more difficult to organize irrigation collectively. We construct a 'potential' measure of the severity of the collective action problem by recording the distance that canals would have to traverse to keep the population where it was before a river shift. When a river shifts, some grid cells will now be irrigated by the new course of the river whereas others will need to build canals. To overcome the endogeneity resulting from the fact that individuals choose to locate near a river, we use our river shift indicator as an instrument for the distance canals will have to cover to keep population in place. We then estimate a standard panel fixed effects model using two stage least squares. Because population lives on average closer to a river before its shift, we find a positive first stage effect: grid cells that experience a river shifting away from them need to build longer canals to keep population constant. In the second stage, we find that greater collective action pressure has a small negative effect on settlement and a large positive effect on canal building. In other words, grid cells that are harder to irrigate collectively are more likely to be irrigated by a canal.

An important challenge to our hypothesis is the collapse of the state, public good provision, and settlement about a 1000 years ago, after the Islamic conquest. Even though Iraqis still stood to gain from public good provision, virtually no canals have been built in the last millennium and even today Iraqis

[5] A final challenge to inference is spatial correlation. We report Conley (1999) standard errors, and find that spatial correlation does not affect the interpretation of our results.

mostly live along the rivers, leaving the productive central plain depopulated. We provide evidence that the Islamic conquest came with institutional changes that removed the state's incentive to uphold its part of the social contract. We first show, by collecting data on institutional quality following Blaydes and Chaney (2013), that the Islamic conquest was associated with a change in political institutions towards despotism. We then argue that, because Islamic governance relied on outside finance, and no longer recruited the local population into its armies, Islamic rulers had no incentive to respond to the demand for public goods. This 'broke' the social contract. In an accompanying paper, we describe the historical scholarship on the collapse. The consensus among historians is that a collapse in state capacity preceded the collapse in settlement. Using tax data, we empirically trace the collapse of public finance after the Islamic conquest (Allen and Heldring, 2018).

The results in this paper paint a positive picture of the capacity of humanity to overcome environmental problems. Iraqis built some of the world's first cities, states and governments at least in part in response to having to deal with a challenging environment. A modern analogy is the international coordination between states to ban chlorofluorocarbons (CFCs) under the Montreal protocol that led to a substantial reduction in the gap in the ozone layer.[6]

This paper contributes to literatures in political economy, environmental economics, and economic history. We contribute to the political economy literature on state formation by testing a 'demand side' theory of state formation, which complements 'supply side' theories of state formation that center on the incentives for coercion and extraction (De La Sierra, 2018; Mayshar et al., 2018; Schönholzer, 2017; Mayoral and Olsson, 2019; Bentzen et al., 2017). In environmental economics, we contribute to the literature on adaptation to climate and environmental change by studying long-run adaptation (Barreca et al., 2016; Carleton and Hsiang, 2016; Auffhammer and Schlenker, 2014). Recent studies estimate on the short-run impact of temperature fluctuations on mortality (Deschenes and Greenstone, 2011; Burgess et al., 2017), conflict (Hsiang et al., 2013), economic activity (Burke et al., 2015), and migration (Deschenes and Moretti, 2009). Scholars have focused on other aspects of environmental change too, such as the fallout of the Chernobyl nuclear disaster (Almond et al., 2009), tropical hurricanes (Emanuel, 2005), and the rising sea level (Balboni, 2019; Nicholls and Lowe, 2006). Acemoglu et al. (2012) and Aghion et al. (2016) study the impact of climate change on technology (policy). In economic history, we contribute to a literature that studies economic development in the ancient past (Barjamovic et al., 2019; Chaney, 2013; Bakker et al.,

[6]The gap is now projected to be fully closed by 2075. See https://ozonewatch.gsfc.nasa.gov/monthly/SH.html (accessed September 2019).

2018). Through our use of shifting rivers as a source of identification, our paper is related to Hornbeck and Naidu (2014) who use a historical flood to identify the effect of the presence of low-skilled labor in the United States south, and Chaney (2013) uses Nile floods to identify the effect of political power of religious leaders.

The rest of this paper is organized as follows. The next section provides the context for our study, southern Iraq and its long-run development. Section 3 introduces our panel dataset and section 4 presents our estimation framework. Section 5 presents the main results of this paper. Section 6 studies collective action. Section 7 traces the collapse of settlement following the Islamic conquest and section 8 concludes. We include three appendices with this paper. The first appendix presents additional results and we refer to this document as the results appendix. The second appendix includes a detailed description of each data source we use and how we integrate all data sources into a unified panel dataset. We refer to this document as the data appendix. Our third appendix is an online 'Atlas of long-run development in Iraq' which describes our panel dataset. It describes each period studied, settlement patterns, river shifts and overall trends in economic development between 5000BCE and today and we refer to the document as our atlas.

2 Setting and context

Geographically, southern Iraq is the arid delta of the Euphrates-Tigris river system and the southernmost part of the Fertile Crescent. Due to its arid climate, this part of the Fertile Crescent is only fertile when sufficiently watered. The area's Greek name, 'Mesopotamia', the 'land between rivers', reflects this dependence on the massive flow of water these rivers bring.[7]

In the rest of this section, we further describe the setting of our study. We focus on patterns of long-run development, on public finance, and on the archeological evidence for the development of a social contract.

2.1 Long-run development

In 5000BCE, Iraqis were practicing subsistence agriculture. Settlements were small, averaging 3,5 hectares in our data (compared to a mean of 17 in our full panel). Writing was invented around 3300BCE and was

[7]The inhabitants of Southern Iraq were over our sample period known as Sumerians, Akkadians, Babylonians, Cassites, Assyrians, Aechemenids, Seleucids, Parthians, Sassanians and under various names of Muslim empires and dynasties. We refer to them as Iraqis and as the area that the Greeks called Mesopotamia as southern Iraq.

coincidental with the prominence of Uruk, one of the world's first cities (Roaf, 1990, p. 170). Around 3000BCE, the first city states develop. We study city state formation in section 5.

In this period, Iraqis built the first ziggurats, large administrative and religious centers that appear in our dataset. We include a photograph of the rebuilt ziggurat of Ur in our atlas. After this period, Sargon of Akkad, who ruled around 2330BCE, unified Mesopotamia for the first time as the Akkadian empire. After invasions destroyed this short-lived centralized state, the next centralization of power occurred under Hammurabi around 1800BCE. We study state centralization in section 5.

The Persians, under Cyrus the Great, conquered Mesopotamia in about 550BCE. After becoming Muslim in the seventh century CE, Baghdad, the new capital founded in 762CE, saw the flourishing of science and cultural life in the 'Golden Age of Islam'. Around 1000CE irrigation infrastructure and settlement collapsed. Today, Iraqis live along the great rivers, and the central Mesopotamian plane where settlement had concentrated for most of history is depopulated. We trace this collapse in section 6.

2.2 Agriculture

The pattern of agriculture was largely stable for the period we study.[8] Elongated fields would be plowed orthogonally to a water source, such that water comes in on the short side of the field. Most fields grew barley, and date palms were grown on the levees of canals and rivers.

2.3 The social contract

In this agricultural environment, access to water was crucial to economic subsistence. For our hypothesis, a key question is whether irrigation could be organized communally? The literature that studies this question ranges from authors arguing that private organization of public good provision is feasible if a series of conditions are satisfied (Ostrom, 1990) to the textbook underprovision of public goods case (see e.g. Samuelson (1954)). Acemoglu (2003) offers a useful thought experiment on the idea of a political Coase theorem, the statement that private individuals, under well defined property rights and absence of transaction costs, can solve collective action problems by contracting. If this theorem applies, collective action problems can be contracted away.

[8] The basic historical patterns in this section and the next are largely on Jursa and Moreno Garcia (2015) and Meyers (1994).

However, Acemoglu (2003) show that typically the political Coase theorem does apply in environments where contracts are hard to write or enforce. The rationale is easy to understand: if contracts are hard to write externalities can not be appropriately allocated and private provision of public goods unravels. We believe that the period of Iraqi history we study is such an environment. Local private canal construction did take place, but the consensus among historians is that the state was instrumental in the provision of irrigation infrastructure (see e.g. Adams (1981)). Contemporaries were of course aware of the threat of overuse or undermaintenance of canal infrastructure. For example, in Hammurabi's famous law code, clause fifty three reads (Hammurabi, 1904):

> "If a man open his canal for irrigation and neglect it and the water carry away an adjacent field, he shall measure out grain on the basis of the adjacent fields."

And clause fifty five reads:

> "If a man neglect to strengthen his dyke and do not strengthen it, and a break be made in his dyke and the water carry away the farm-land, the man in whose dyke the break has been made shall restore the grain which he has damaged."

In the rest of this section, we provide an overview of the organization of public finance and the development of a social contract. In section 6 we quantify the severity of the collective action problem at a local level and show that canal building is concentrated where it is harder to organize irrigation communally.

Our knowledge on the fiscal state starts from around 2000BCE.[9] The main sources of revenue were indirect taxes, such as harbor and road duties, taxes in kind on agricultural output (mostly livestock), and labor services, which were the largest tax base. Individuals were required to work on construction and maintenance of canals, construction of public buildings or military service. Tax collection was almost uniformly done through tax farming. For example, in the third millennium BCE, there were about twenty provinces, each led by a governor. The governor had a quota of taxes to deliver under his tax farming contract, and in turn, farmed the door-to-door tax collection out to lower officials. These lower officials raised taxes in exchange for overseeing local public good provision (see below for an example of this arrangement). This system was monitored by a large number of accountants and scribes that recorded every tax payment and compared it to expected payments under the tax farming agreements.

[9]The source material for our knowledge of these topics typically come from administrative records inscribed on clay tablets. For the period we study, government was preoccupied with tax collection and public administration: about 80% of all surviving clay tablet records from ancient Iraq are administrative, such as contracts, settlements of accounts and letters dealing with business.

From about 1500BCE, with the centralization of the state and the formation of a single unified political entity ruling all of southern Iraq, the nature of taxation changed. The ruler claimed ownership of all land, only to give it back to the occupiers in exchange for labor services and other taxes (such grants are referred to as fiefs). This is essentially a feudal system as it existed in Europe after the fall of the Roman Empire. As the power of the centralized administration grew, so did indirect taxes on transportation, innkeeping and baking, for example.

From about 500BCE, states taxed temples, private urban households in a direct head tax, and continued the practice of demanding labor services and other taxes in return for the usufruct of the land. The practical organization of taxation was increasingly formalized, and we have surviving records that describe tax collection in detail.

As before, the state farmed out tax collection to elites, who in turn farmed out the day to day collection of taxes to lower level functionaries. Around this time, these wer called *gugallus*. Recruited from the local population, their title translates as 'canal inspector'. They were responsible for canal maintenance and tax collection, evidencing the intimate relationship between the two in Mesopotamian government organization (see detailed cuneiform tablet references in Jursa and Waerzeggers (2009)). In fact, the contracts that survive that govern the position of gugallu explicitly mention the tax-for-irrigation social contract. Although we do not know this for sure, it is very likely that the lower tax officials that we discuss above, operated under similar arrangements (Jursa, 2010).

We have reproduced an example of a clay tablet that captures the key relationships underpinning the social contract in Figure 1. This clay tablet originates from about 500BCE and we provide a translation underneath the figure. It cites the investiture of the estate manager by the governor: "the gift (bīt qīpti) of Nabû-nādin-šumi ... is at the disposal of Nergal-uballit"); The responsibilities of the bureaucrat maintaining public goods: "He guarantees for guarding the canal and taking care (hâru) of the royal road."; and the tax under the tax farming contract to the governor: "Every year, Nergal-uballit will pay to Nabû-nādinšumi, the governor of Borsippa, (these) two minas of silver for the gugallu-office." and several taxes that the estate manager can raise from the local population (such as sheep, clothing and dates). For a full list of taxes that were levied in the sixth century BCE, see Jursa (2010).

At the level of the state, kings were directly involved with the management of these systems as well. The tablet in Figure 1 is signed with the king, Amīl-Marduk, as a witness. Other rulers prided themselves on canal construction. For example, Nebuchadnezzar, the biblical ruler of Babylon, claimed, for example, that: "As for ... the Eastern canal of Babylon, which since days far past [had been abandoned]: I sought out its course and rebuilt ..." (cited in MacGinnis (2018, p. 43)).

Under the reign of Darius I, who died in 487BCE, a push was made to substitute in-kind payments to payments in silver. From then on, in-kind taxation disappeared and was substituted with money payments. Labor services did continue and were used for construction and military purposes predominantly. We stop our discussion of government functioning here since by 0CE the rivers have largely reached their current positions and, aside from the collapse of rural settlement studied below, we do not study further periods in detail.

In this section, we provided some case study evidence for the presence and form of the social contract in ancient Iraq. In exchange for taxes, the state provided and maintained public goods. These public goods, we hypothesize, helped citizens overcome the challenges posed by their environment. We test this hypothesis after we describe our data and estimation framework in the next sections.

3 Data

This section describes the panel dataset of environmental change, settlement, state formation and public good provision that forms the basis of the empirical results in this paper.

Source material. We are able to construct our panel due to the availability of about a century of archeological work in the area largely undertaken by the Oriental Institute at the University of Chicago (Adams, 1957, 1965, 1981). We digitized their entire works, and have complemented the resulting dataset with archeological data reconstructing the flow of the Euphrates and Tigris over time (e.g. Gasche et al. (2002)), studies cataloging all evidence we have on historical buildings (Heinrich, 1982, 1984; Meyers, 1994) and data on the hierarchy of city states and the formation of centralized states (Roaf, 1990).

The focus in this section is on the construction of the panel. The details concerning the combination of several archeological surveys, other data sources, and geographical variables are described in the data appendix. This appendix also provides detailed source references for all variables we use in the empirical part of this paper.

3.1 Unit of observation and the use of archeological data

Figure 2 provides a map that zooms in successively from the Middle-East to our sample area. This map shows Baghdad and the modern courses of the Euphrates and Tigris rivers.

3.1.1 Unit of observation

The cross-sectional unit of observation in this paper is a 5x5 kilometer grid cell. We restrict the sample to cover the union of the archeological surveys that have over time been carried out in southern Iraq. This procedure results in a dataset of 1,325 grid cells covering most of the area between the modern Euphrates and Tigris rivers between Baghdad and modern Basra. Historically, the Basra area was on the coast since the level of the Persian Gulf was higher.

We refer to the area covered by these grid cells as our sample area. Figure 1 in the the data appendix provides a map. Our atlas provides maps of the fluctuating coastline over time.

3.1.2 Unit of time

We observe each grid cell for each of 31 historical periods, covering 5000BCE until the present. We code our time periods following conventions in archeology. Table 1 of our data appendix gives the periodization we use. Following archeological conventions for periodization allows us to chronologically tie together different archeological surveys and our reconstruction of the moves of rivers. For example, the 'early Uruk' period extends from 3900BCE - 3500BCE. As another example, the Sassanian period extends from 224CE - 651CE and covers the Sassanid empire that had conquered our sample area from the Parthians, in 224CE. In our atlas, we provide maps of settlement, cities, and canals for each period.

A natural concern is the possibility of the archeological periodization depending on changes in an outcome variable of interest. We do not believe that this is a concern because, as we show in section 4.1, a river shift is is uncorrelated with lagged changes in development. We nevertheless provide a robustness table in the results appendix that creates 'synthetic' equal length periods. Results are unchanged.

3.1.3 Using archeological data

We built our panel to study institutional adaptation to environmental change over the long run. Using archeological data allows us to trace the effects of environmental change to settlement, state building and public good provision for periods for which no written records survive. Since states typically collect data, studying state formation is particularly hampered by lack of data, but the development of states can be measured by archeological remains.

Using archeological data also has some potential drawbacks, which we list and discuss here. First, archeologists select excavation sites in anticipation of finding material remains. This process may lead to a selection problem in the sense that we would only have data for those parts of the sample area that were (thought to have been) more heavily populated. For our main data sources, the surveys of settlement, rivers and canals carried out by the Chicago Oriental Institute, we do not face this problem. These were designed to be 'sweep surveys' covering the full extent of their respective study areas. Second, there may be significant measurement error in both the location of finds, as wind and water could shift archeological remains to new locations, and in the timing of remains, since our data predate the advent of radiocarbon dating methods. In our case, spatial measurement error is likely to be limited since in the Iraqi desert settlement leaves behind distinct mounds, or elevated small hills, due to the debris and other waste that human settlement left. These mounds are visible in the landscape today, and have been identified through archeological excavation and verified using models based on satellite imagery (Hritz, 2010). The data appendix describes the methodology used by archeologists for identifying human settlement in more detail. Temporal measurement error too can be substantial, especially without the use of radiocarbon (C14) dating methods. The archeologists excavating Iraq have devised a dating method around styles of pottery. A new find will be matched to similar finds based on production style. Examples of production styles can subsequently be linked to specific dates/periods using finds that can be dated through, for example, an inscription. This method has been extensively researched and refined in the archeological literature, and we do not believe that temporal measurement error affects our results. Finally, archeological data may suffer from differential survivor bias in the sense that certain types of remains may be more prone to decay or theft. For our data on buildings, this concern is unlikely to affect our results because typically archeologists recover the entire stratigraphy of an important building site. This means that they drill vertical holes and inspect layers to reconstruct the timeline of occupation, and will therefore recover each stage of occupation and not just the ones visible from the surface.

3.2 Data and measurement

In this section, we describe our main treatment variable, an indicator that measures if a river shifted away from a location, and the outcome variables used in this paper.

3.2.1 Treatment: measuring environmental change

Figure 2 maps Iraq's main rivers, the Euphrates and the Tigris. In 5000BCE, the two rivers were one (see our atlas, section 1). The Ur-river, as their combined flow was called, branched down the center of our sample area. Because the flow of the rivers slowed down as they entered the flattening plain, sediment deposits started building up in their beds. These deposits got pushed to the banks of the rivers, forming levees.[10]

The volume of river flow is largely determined by rainfall in Turkey and Syria, where they originate.[11] When downstream flow increases suddenly after heavy upstream rainfall, the river would at times burst through the levee. Often, the resulting decrease in flow speed (as the water now covers more area) led to sediment deposit which would fill up the opened gap in the levee. Sometimes the breach would be permanent, and from the breach the river would find a new course in the landscape. Such river shifts can be occur in the span of weeks because the waters need to swell enough to break through and not fill back up again. The river shift around 1800BC, which we study below, happened swiftly, for example.[12] We know of shifts that are more gradual, with one river branch gradually silting up and another branch becoming more prominent.[13]

Table 1 provides an overview of each river shift in our sample. In total, we identify ten river shifts. In the data appendix, we provide a full discussion of what we know about each river shift, and the atlas maps the situation before and after each river shift between 5000BCE and today.

In order to capture the effect of a river shift at the level of the grid cell, we implement the following procedure. For each panel period t, a grid cell c is 'on a river' if its centroid is within five kilometers of the nearest river.[14] We define grid cell c as being treated in period t if c was on a river in period $t-1$ and no longer in period t. Measuring treatment this way captures the idea that settlements that had their own independent water source can now only farm productively if water is brought in through a canal.

[10]The discussion in this chapter is based on chapter 1 in Adams (1981).

[11]For the Tigris, high water usually comes in April. For the Euphrates, early May. Evaporation and upstream water use also determine downstream water flow.

[12]For an overview of what we know of the sudden change in the Euphrates at this time, see Adams (1981, p. 18).

[13]We provide an example of such a move around 3000BCE in the data appendix.

[14]As a robustness check, we can refine what it means to be 'on a river'. We add the condition that aside from a centroid being within five kilometers of a river that river has to be uphill, so that water flows down towards the centroid. In practice, settlements close to rivers could farm next to the river and settle a bit further away. Results do not change much when we implement this idea. Results are available upon request.

3.2.2 Outcome variables

In this section, we describe each outcome variable used in section 5.

Development. As a measure of development we use the count of settlements.[15] For each period t we count the number of settlements in grid cell c. In the results appendix, we use the fact that we have (limited) information on the extent of settlement in hectares to test the robustness of our results to accounting for the size of settlements.

Since we have data going back to the earliest human occupation in the region around 5000BCE, we can use our settlement data to paint a unique picture of of economic development in Iraq. In Figure 4 we have plotted the total number of settlements (excluding cities) over time. The resulting time-series pattern shows a marked rise and decline pattern. We consider this time-series of independent interest because it complements the scarce data we have on very early development from city size data (McEvedy and Jones, 1978) and GDP estimates (Bolt et al., 2018). In the rest of this section, we will give two examples of what our settlement data look like within a period. Our atlas provides maps for each period separately.

For example, in the 'Early Uruk' period (3900BCE - 3600BCE), 202 out of 1,325 grid cells are settled. On average, a settled grid cell has 2.3 settlements and the maximum number of settlements is 13. Aside from smaller settlements, we have identified eleven cities that were inhabited in this period. Uruk is the most important, but other well-known examples are Ur, Nippur and Sippar. In the Middle Uruk period (3600BCE - 3500BCE), 225 grid cells are inhabited, and the city of Eshnunna (modern Tell Asmar) has been founded. In the Late Uruk period (3500BCE - 3100BCE), 228 grid cells are inhabited, and the city of Tutub (modern Khafagi) has now become populated.

We can contrast these data with, for example, the period corresponding to biblical Babylon ruled by Nebuchadnezzar. In our data, this period lasts from 626BCE - 539BCE and is called the Neo Babylonian period. In this period, we have 250 grid cells inhabited with, on average, two settlements per grid cell. Uruk is still inhabited but much less important than Babylon, Kish and a number of other new cities. We have 14 cities in total in our sample for this period.

States and bureaucracy. We measure the development of states in three different ways. First, we

[15]Using population or settlement density as a measure of economic development is well established, see e.g. Acemoglu et al. (2002)

measure the presence of city states and centralized states. To measure the presence of a city state, which varies in the cross-section, we record whether a grid cell is part of a state in the time-series periods that have multiple (city) states in the sample area. We define being part of a city state by an indicator. This indicator is equal to one if the nearest city to a grid cell has at least one administrative building dedicated to government.

Since states throughout most of Iraqi history did not have enforced outer borders, we can not simply map out larger states. To understand when our sample area became part governed by one centralized state, we rely on information that links cities together in dependency relations to map out states. City A is dependent on city B if a formal dependency has been preserved in the records.[16] A dependency can be conquest and occupation, formal submission to authority, or de facto suzerainty through the threat of superior force. If the nearest city to a grid cell has at least one administrative building and, in addition, it is part of a network of cities, either as capital or as dependent city, we consider this grid cell part of a state. If all cities are part of one network, we consider our sample area to be ruled by one state. Section 7 of the data appendix presents this process in more detail, and contains a visualization.

Second, we measure the distance to the capital city of the state a grid cell is part of. This distance measures proximity to the focal area of the state and varies within a cross-section (even when the entire sample area is under one centralized state). Since capitals change and move, we can measure the response of the center of administration to river shifts.

Finally, in order to measure bureaucratic infrastructure, we coded up a separate survey of all archeological remains of palaces and other administrative buildings from Heinrich (1982), Heinrich (1984) and Roaf (1990). For a large number of cities in each period, we know the number of administrative buildings and the size of each administrative building. These data are fully described in the data appendix. As an example, the palace of biblical Nebuchadnezzar (the 'Hauptburg' in the terminology of the excavation team) was built in the Neo Babylonian period and was about 150 by 150 meters and had about 125 rooms. The ruins can today be found on the Babil mound near modern Hillah. In our dataset, we record this palace to be in use from 626BCE until about 150BCE based on its description in Heinrich (1984).

Public good provision. We measure public good provision by the network of canals that watered parts

[16] Data come primarily from Beek (1962). We describe the full procedure in the data appendix. We also separately describe the records for each city in our sample there.

of the sample area that would otherwise have been unsuitable for agriculture. Most canals are recorded as part of the Chicago Oriental Institute's excavations. We extend and cross-reference the archeological data with satellite imagery that shows the former courses of dried up canals. We code an indicator equal to one if the centroid of grid cell c is within five kilometers of a canal. This indicator captures whether a grid cell is 'on a canal' or not. We describe the full coding procedure for the canals in the data appendix.

Collective action. We measure collective action pressure simply by the change in distance to the nearest river before and after a river shift, for grid cells that were inhabited before the river shift. If a river shifts little, there is less distance to cover with canals to keep the population in place, and therefore fewer problems of public good provision (for canal construction) or collective action (for maintenance or upstream overuse of water). We introduce this idea in more detail in section 6.

3.3 Summary statistics

Table 1 presents summary statistics across the 31 periods and 1,325 grid cells (n = 41075). About 2 percent of grid cell by period observations see a river shift. The main variables used in the paper are described above. The remaining listed variables are geographical covariates, such as rainfall and temperature, which are described in the data appendix.

4 Estimation framework

In this section, we discuss how southern Iraq's geography induces collective action problems, and how we estimate the effect of changing river courses on the formation of states, public good provision and the solution of the environmental challenges. We then present our estimation framework, a simple dynamic panel differences-in-differences design, before discussing challenges to identification within this framework.

4.1 The geographical basis of our treatment

Figure 5 presents a three dimensional aerial view of the sample area. The river courses as they existed in 5000BCE are in red, and the contemporary river courses are in blue. The hypothesis of this paper is that, as these rivers shift between their historical and modern beds, individuals have a demand for the solution of the collective action problem, and we expect the formation of states to be concentrated where rivers move. But why would farmers not simply pick up and move to where the river went?

We shed light on this question using geographical data on temperature, rainfall, and geographical suitability for growing barley, the main staple crop of the area. We regress these measures, in a cross-section, on an indicator that equals one if a grid cell has ever experienced a river shift. These regressions show whether places that are in the center of the plain, where river shifts are concentrated, are different from places where fewer moves take place. Note that for our main empirical analyses, we include a full set of grid cell fixed effects, accounting for such cross-sectional, time-invariant differences.

Formally, we estimate the following equation, using OLS:

$$Y_c = \alpha + \beta \times rivermove_c + \varepsilon_c \tag{1}$$

In this model, Y_c is an outcome of interest, such as rainfall in millimeters, for grid cell c. $rivermove_c$ is an indicator equal to one if grid cell c ever experienced a river shift. ε_c is a heteroskedasticity robust standard error. Because we use grid cells as a unit of observation, and because typically geographical variables such as the ones we use here are interpolated over space, we report Conley (1999) standard errors. We compute these standard errors correcting for arbitrary spatial correlation across grid cells within a 100KM radius.

Table 3 reports estimates of this model. Columns present different dependent variables, and the first row presents estimates of β in equation 1. Columns 1 and 2 show that, on average, the center of the sample area experiences lower rainfall, and higher temperatures. Column 3 shows that when relying only on rainfall, the center of the sample area is less suitable for growing barley (the main local staple crop). In other words, the part of our sample area where treatment is concentrated is less productive and more arid. Column (4) provides evidence, however, that when irrigated the center of the plain is more productive. This last result is in line with our historical data that show that when rivers move away, settlement tends to stay in the center of the plain, rather than moving with the rivers. Due to interpolation in the geographical outcome data, Conley (1999) are higher throughout, but results stay within conventional significance levels. Taken together, the results in this table show that there is a productivity differential that is realized when irrigating the center of the plain.

We exploit the river shifts and the fact that there is productivity incentive to stay in the center of the plain as the geographical basis for testing our hypothesis: when a river shifts away, individuals would like to stay where they are and farm, but they can only do so productively when irrigating their land.

For a small number of communities, we know that the investment to build canals, and their subsequent maintenance, may be organized communally (Ostrom, 1990; Ellickson, 1991). For larger-scale organization, however, the standard public goods/collective action problems of underinvestment and overuse apply. We hypothesize, therefore, that river shifts create a *demand* for the solution of these collective action problems, and may lead to state formation, and public good provision, that will alleviate the collective action problems. The rest of this paper is dedicated to testing this hypothesis.

4.2 Estimating equations

In this section, we introduce the estimating equations for this paper. To assess balance on lagged outcomes, we estimate a simple fixed effects panel regression. To estimate the causal effect of a river shift, we estimate a dynamic panel differences-in-differences model.

4.2.1 Timing

We record all our outcome variables and covariates for period t at the end of the period. We assign a river shift to a period in two ways. Either the timing of the shift happens to coincide with a period change. In this case, we assign it to that period, so that we measure the impact of a river shift in period t in period t and not in period $t+1$. When a river shift occurs away from the start of a period, we assign it to the start of the period we are sure it has happened by. A full description of this procedure is in the data appendix and table 1 records the assigned period for each river shift.

4.2.2 Panel fixed effects model

To assess balance of treatment on lagged outcome variables we estimate a simple panel fixed effects model, of the following form:

$$Y_{ct} = \gamma_c + r_t + treated_{ct} + \varepsilon_{ct} \tag{2}$$

Y_{ct} is an outcome of interest for grid cell c in period t. γ_c is a vector of grid cell fixed effects. r_t is a vector of period fixed effects. $treated_{ct}$ is an indicator equal to one if grid cell c was on a river in period $t-1$ and is no longer on a river. ε_{ct} is a heteroskedasticity robust standard error, clustered at the grid cell level. Since we use artifical 5x5 kilometers grid cells as our unit of observation, we have to account for spatial correlation across our grid cells. We report Conley (1999) standard errors throughout. We include grid cells in a 100KM radius in the computation of these errors.

4.2.3 Panel difference-in-differences model

We study the causal effect of a river shift in a dynamic panel difference-in-differences design that compares grid cells that are on a shifting river to grid cells whose nearest river is stationary, before and after the river shift. We estimate both an average effect across all river shifts and focus on several individual river shifts as separate experiments. After introducing the main estimating equations, we establish that, before a river shift, grid cells that will be treated look similar to ones not treated.

We estimate a stacked panel difference-in-differences model. Intuitively, for each period t, we construct a short-run panel covering two periods before treatment and one after. We refer to such a short term panel as an 'experiment' centered on period t. We then stack each of these 'experiments' into a larger panel. Formally, the equation we estimate has the following form:

$$Y_{ctk} = \gamma_c + \sum_{k=-2}^{0} \beta_k \times \mathbb{1}(period_k) + \sum_{k=-2}^{0} \beta_0^{treatment} \times \mathbb{1}(period_k) \times treated_{ct} + \rho_{ck} + \varepsilon_{ctk} \qquad (3)$$

Here Y_{ctk} is an outcome of interest for grid cell c in the experiment centered on period t and period relative to treatment k.

γ_c is a vector of grid cell fixed effects, which are constant across periods k and experiments t. $\sum_{k=-2}^{0} \beta_k \times \mathbb{1}(period_k)$ is a vector of period-relative-to-treatment fixed effects multiplied with period-varying coefficients β_k. In our analyses, we omit $k = -1$ so that we express all effects relative to the last pre-treatment period. $\sum_{k=-2}^{0} \beta_k^{treatment} \times \mathbb{1}(period_k) \times treated_{ct}$ is the vector of period-relative-to-treatment fixed effects multiplied with an indicator $treated_{ct}$ which is equal to one if grid cell c is treated in period $k = 0$ in experiment t. This indicator is time-invariant within an experiment and the $\beta_k^{treatment}$ capture the time-varying effect of being treated in $k = 0$ through their multiplication with the period period-relative-to-treatment fixed effects. Since we express all effects relative to period $k = -1$ we obtain two coefficients of interest: $\beta_0^{treatment}$, the treatment effect for those treated grid cells in the treatment period and $\beta_{-2}^{treatment}$ the treatment effect for those treated in the treatment period $k = 0$ in period $k = -2$. Whereas the latter coefficient measures pre-trends relative to period $k = -1$, $\beta_0^{treatment}$ is the coefficient of interest in this model: the measured effect of a river shift on outcome Y_{ctk}, across experiments t.

This model does not assume that there are no average differences between treatment and control. These differences are absorbed by the unit fixed effects γ_c. Rather, we study grid cells over time, comparing the average difference in the outcome of interest post-treatment relative to pre-treatment, across treatment and control, across experiments.

ρ_{ck} is a vector of period-relative-to-treatment by covariate fixed effects. In most specifications, we include covariates for archeological surveys, capturing differential effects of different surveys over time, as well as rainfall and temperature. If, for example, the temperature drops on average before a river shift, then period-relative-to-treatment by rainfall fixed effects will pick up these trends. Finally, ε_{ctk} is a standard error, clustered at the grid cell level. We also report Conley (1999) using a 100KM cutoff. We find these standard errors are consistently higher than clustered standard errors, but nowhere high enough to threaten inference.

We present the main results of this paper graphically, plotting $\beta_{-2}^{treatment}$ and $\beta_{0}^{treatment}$ and their confidence intervals, and in tabular form. Before introducing the plots and tables in section 5, we discuss sample restrictions, potential challenges associated with estimating the model introduced in this section and we introduce our study experiments.

4.2.4 Sample restrictions

We employ four sample restrictions throughout all analyses. First, we drop grid cells that were on a river before and saw a river shift away but also saw a new river branch move closer to them. In other words, if for grid cell c the river branch the unit used to be on in period $k-1$ moves away but a new branch moves in period $k=0$ the estimated treatment effect will pick up both the effect of a river moving away and the new river moving in. In practice, this rarely happens and the treatment effects are similar with and without this restriction. Second, we drop grid cells that are treated in both $k=0$ and in one of the pre-periods. This would correspond to a situation in which a river shifts away and another river branch shifts into a grid cell, only to shift away again in the next period. For this restriction too, treatment effects are similar without. Third, we drop grid cells for which our archeological base data indicated that a limited survey, rather than a full scale sweep survey, was carried out. Finally, we drop data post-1918. These correspond to the archeological period termed 'Recent' (see table 1 in the data appendix).

In the appendix, we restrict our control group to all grid cells c that are on a river in $t-1$ and are still on a river in t. The difference between the main control group and this restricted control group is the inclusion of untreated cells more than five kilometers away from a river. These are included in the main control group and omitted in the restricted control group. Results across these two control groups are similar for all analyses.

4.3 Identification assumptions

The key identification assumption in this model is that, conditional on fixed effects and (time-varying) covariates, a river shift is exogenous. This assumption, within the context of our model, implies parallel pre-trends. The assumption would be violated if, for example, there are shocks that affect both the timing of river shifts and outcomes. This may occur if states manage to manipulate river flow in such a way that future changes are now dependent on contemporary shocks resulting from human interference.

Throughout all analyses, we show estimates of pre-trends by reporting treatment coefficients for $k = -2$ relative to $k = -1$. If there were non-parallel pre-trends, we would expect a significant treatment effect in $k = -2$. This would show that grid cells that are going to be treated in $k = 0$ look different in $k = -2$. We do not find such differences.

Another way to understand the issue of pre-trends is to regress lagged outcomes on treatment indicators. If treatment in $k = 0$ correlates with outcomes in $k = -1$ or $k = -2$ this again means that grid cells that are going to be treated in the future look different before treatment.

We study pre-trends through this last exercise in table 4, which provides estimates of equation 2. Columns vary outcome variables and the first row provides estimates of $treated_{ct}$, the measured effect of a river moving away from grid cell c. We focus on lagging development and public good provision. If a contemporary river shift predicts lagged settlement or public good provision, we are concerned that human interference in the environment in the past precipitates future river shifts, and that therefore the identification assumptions that allow us to interpret estimates of treatment effects in equation 3 as causal are not met.

Columns (1) and (2) of Table 4 provide results for lagged settlement, and columns (3) and (4) provide results for lagged public good provision in the form of the canal indicator introduced above. All point estimates are standardized. The point estimates are all essentially zero and insignificant. These results provide support for our claim that the identification assumptions underlying our empirical strategy are met. The main results in this paper build on this idea by estimating the effect of a river shift, for both the full panel and for three distinct study periods. We will now introduce these study periods.

4.4 Selection of experiments

In the results section, we present results for our full panel dataset, and then we study three individual river moves separately which we refer to as 'experiments'. The main reason for this split is that we want to study the *process* of state formation through its qualitatively different stages. In addition, splitting our sample along the time-series dimension allows us to focus on the river shifts that line up with changes in archeological periods. Table 1 lists each river shift, and the reason why we include this river shift as a separate experiment or not. The data appendix gives a full description of everything we know about each river shift. Aside from running regressions using the full panel, we study three experiments, which we describe in this section.

4.4.1 The formation of city states

The first experiment we study is the 'Early Dynastic I' period, which lasts from 2900BCE - 2700BCE. Around 2900BCE a river shift took place, which we map in Figure 6. Just before this period, the first city states in the plain had started to form around Eridu, Ur and Uruk. We study whether city states were more likely to form and consolidate where collective action pressure, induced by a river shift, was higher.

4.4.2 The formation of a centralized state

The second experiment we study is the 'Old Babylonian' period, which lasts from 1800BCE - 1600BCE. Around 1800BCE a river shift took place, which we map in Figure 7. A few periods earlier, in the Akkad period (2350BCE - 2150BCE) the first centralized state ruling all of our sample area formed (the 'Akkadian empire'). Before our study period, in the 'Larsa' period (1900BCE - 1800BCE), this state collapsed, and we study the reformation of a centralized state centered on Babylon in the Old Babylonian period.

4.4.3 Placebo: external invasion

The final experiment we study is a placebo experiment. The 'Middle Babylonian' period (1200BCE - 750BCE) was, as the previous experiment, preceded by a power vacuum. A river shift occurred at the start of the period, which would create an experiment like the previous one, in state formation. We map this move in Figure 8. However, at the same time, the Elamites, a group of people from Iran, invaded. They did not destroy any cities but did stifle any attempts at state formation by suppressing the formation of new cities and the construction of state infrastructure. We, therefore, treat this period as a placebo. Even though the incentives created by the river shift were the same as in other state formation periods, the Elamites prevented these from being implemented, and we, therefore, expect to see settlement decline as a consequence of a river shift, since no canals could be built to sustain settlement.

5 Results

In this section, we present the main results of the paper. In line with our hypothesis, we find that Iraqis adapted to environmental change by forming the first cities, states and governments in history. These states built canals, which allowed Iraqis to farm the otherwise unproductive desert.

5.1 Results for settlement

We first provide estimates of equation 3 using the count of settlements as the dependent variable for the full panel, ranging from 5000BCE until 1918. In Figure 9, we present the estimates of the treatment effect of a river shift on settlement in the treatment period $k = 0$ and in the pre-periods, to assess the parallel trends assumption. The y-axis measures standardized (mean zero, unit standard deviation) effect sizes and confidence intervals. This figure shows that there are no significant differences between treatment and control before treatment occurs. After treatment, treated cells are on average less densely settled.

Table 5 column (1) shows the same results in table form. In column (2), we restrict to 'high environmental pressure' grid cells, which are grid cells that receive rainfall below the 75th percentile of the distribution of rainfall.[17] In column (3), we restrict the 'low environmental pressure' grid cells, which are grid cells that receive rainfall above its 75th percentile. The first row provides point estimates of $\beta_0^{treatment}$, the main treatment effect. All estimated effects are in standard deviations, and expressed relative to period $k = -1$. Below the estimated treatment effect, we provide p-values for the presence of a pre-trend. These p-values are computed using the point estimates and standard errors estimated for $\beta_{-2}^{treatment}$.

The point estimate in column (1) shows that, on average, over the entire sample, when a river shifts away from a grid cell, settlement goes down in that grid cell relative to grid cells also on a stationary river. This decrease is economically meaningful. Being treated reduces settlement by about one-tenth of a standard deviation, which is about one-third of its mean. Columns (2) and (3) suggest that this effect is

[17] The 75th percentile is equal to 14mm. This is about the lower bound of rainfall for the growing season in the rainfall station data presented in Adams (1981, p. 12).

concentrated in areas that are unsuitable for rain-fed agriculture. In grid cells that can substitute, at least to some extent, irrigated agriculture with rain-fed agriculture the average effect across river shifts is not significantly different from zero.

Robustness. In the results appendix, we implement several robustness checks, which we will only briefly discuss here. First, we show that our results are not due to the inclusion of time-varying covariates. Second, we should that using the size of settlements, rather than their count, produces qualitatively similar effects to our results here. Third, we show, using 'synthetic' equal sized periods, that our use of archeological periods as the time-dimension in our panel does not affect our results. Finally, we restrict the control group to only include grid cells that are within five kilometers of a stationary river, rather than cells equidistant to a stationary river. Results are very similar throughout.

The next section uses several measures of the presence and capacity of the state as outcome variables to directly show that states are being built where rivers move and that public goods are provided to allow settlement to remain where it had been in previous periods.

5.2 Results for state formation

In this section, we trace the formation of states in response to a river shift through the time-series experiments introduced above. First, we show that during the city states period, a river shift leads to the formation of city states, and the construction of more, and larger, government buildings in the cities closest to the area where the river shifted. We then show that, for the experiment in which city states consolidate into one centralized state, the capital city relocates closer to the area where the river shifts, and that more, and larger, administrative buildings are constructed in this new capital. Taken together, this section shows that states are being built in response to a river shift.

Figure 10 provides estimates of equation 3 for the city states experiment, $t = 8$. The dependent variable is an indicator equal to one if grid cell c was part of a city state. The figure shows that, when a river shifts, away, a grid cell is more likely to be part of a city state.

The result in this figure corresponds to column (1) of Table 6. In column (2) we use the number of such buildings in the nearest city as the dependent variable and in column (3) we use the total size of all such buildings as the dependent variable. Taken together, these variables measure construction of state infrastructure across the sample area, and we test whether river shift cause the establishment of new states (column (1)) or expansion of state infrastructure (columns (2) and (3)).

The point estimate in column (1) shows that, in response to a river shift, grid cells are 7 percentage points more likely to be part of a city state, relative to a mean of thirteen percent. The estimates in column (2) and (3) show that the effect of a river shift on state building also works along the intensive margin: the number of administrative buildings, and their floor area both increase by about a third. In our data we see for example that a new royal palace in being constructed in Adab, while the Eanna Ziggurat was built in Uruk.

We then focus on the consolidation of city states into a centralized state. In $t = 15$, the 'Old Babylonian' period, all of our sample area came under the Babylonian state. At the beginning of this period, the Euphrates river shifted from the center of the plain outward, in the northern part of our sample area. In Table 6, we ask whether the state infrastructure of the new centralized state is concentrated in the part of the sample area where the river shift took place. In column (1), we use the distance to the new capital, Babylon, as the outcome variable. In columns (2) and (3) we use the number and size of administrative buildings in the new capital as the dependent variables. The point estimate in column (1) suggests that, on average, treatment results in the capital being about fifteen kilometers closer. Since the new capital in Babylon took over this role from several regional capitals in $k = -1$, this implies that Babylon is on average closer to the treated area than the former capitals were. Additionally, government infrastructure was built up in the new capital, both in terms of the number of administrative buildings and in their size (columns (2) and (3)). We see these results in the historical record. Hammurabi, the ruler most associated with this period, did not only make Babylon the capital of his powerful empire, moving it from Dur-Kurigalzu and several local capitals, but also built the extensive Sudburg Palace and the Old Ziggurat in Babylon. These two buildings far exceeded, in size, the administrative buildings in the older regional capitals of Eshnunna and Larsa.[18]

Taken together, we see that a river shift leads to the building and consolidation of some of the world's first states. In the next two sections, we first show that where rivers move, more public goods are provided. We then focus on collective action in the last results section, where we provide evidence that collective action is at the root of the causal effects estimated here.

[18] In our placebo period, there is no change in either the location of the capital, or the number of administrative buildings across the plain.

5.3 Results for public good provision

In this section, we show that river shifts affect the construction of canals. These canals allow settlement to remain in the most productive parts of the sample area, and likely drive the absence of a drop in settlement as a result of a river shift that we showed in Table 5. Figures 6 through 8 map the canals we study in this section.

Table 8 uses the 'on a canal' indicator introduced above as the dependent variable. This indicator is equal to one if a grid cell is within five kilometers of a canal in a period. Columns are restricted to the city states, state formation, and placebo periods. The first row contains the estimated treatment effects, as before.

For column (1) the estimated effect of a river shift is positive and significant. We visualize this result in Figure 8. It suggests that a river shift increases the probability of being on a canal by about 14 percentage points, or about half its mean. We find the same effect for the state formation period (column (2)), and no effect for the placebo period (column (3)). Taken together, we find that in response to a river shift, canals are being built that allow settlement to remain in the most productive parts of the sample area.

Robustness. In the appendix, we show that these results are robust to restricting the control group to cells that are within five kilometers from a stationary river.

5.4 The effect of a river move when there is a state

In Table 9 we re-estimate the effect of river shifts on settlement, for each of our experiments separately. Consistent with our hypothesis, we find that sates offset the negative effect of a river shift on settlement.

In column (1), we restrict to the city states experiment. This means that, in terms of equation 3, we focus on a single experiment $t = 8$. In column (2), we restrict to $t = 15$ and in column (3) we show placebo results, $t = 17$. We find a marginally positive effect in the city states experiment and an insignificant positive effect for the centralized states experiment. For the centralized states experiment, we provide a visual representation of the results in column (2) in Figure 12. In column (3), the placebo period, we do see a drop in settlement of about a third of a standard deviation as a result of a river shift. This drop is approximately equal to the mean of the number of settlements over the entire panel.

These results close out our argument. Across all river shifts, we find a negative effect of a river shift on settlement. But when states form and canals are built, the negative effect of a river shift is offset, and settlement stays constant. We have hypothesized that behind the demand for states lies a collective action problem which prevents farmers from organizing irrigation collectively. In the next section we study this claim.

6 Mechanisms: collective action

We hypothesize that river shifts, through the need for irrigation, create a collective action problem. We also hypothesize that when the scale of coordination to build irrigation infrastructure is small, canals may be provided communally. At larger scales, coordination problems may prove prohibitive. In this section, we propose a measure of the severity of collective action and test these predictions. We find that canals are built to where the collective action problem is more 'severe'.

We create a 'potential' measure of collective action by recording the distance canals would have to cover after a river shift to reach inhabited grid cells, irrespective of whether they actually get built. For places that are further away from rivers, this measure will be higher, capturing the idea that there are higher levels of coordination necessary to reach this grid cell. Empirically, we re-estimate our panel fixed effects regression (equation 2), with some modifications. We replace the binary treatment of being on a river with distance to the nearest river, and we restrict the sample for period t to those cells that were inhabited in period $t-1$. Because population can choose its location relative to a river, distance to the nearest river is endogenous. We instrument distance to the nearest river with our indicator that captures whether a grid cell was on a river in $t-1$ and saw a sudden river shift period t. Note that the resulting first stage relationship is not mechanical because away from the five-kilometer cutoff used to define the 'on a river' indicator, rivers may move further away, move closer, or stay put.

The idea of this approach is to regress settlement and public good outcomes on our measure of collective action, distance to the nearest river for inhabited cells, and to use our movement indicator to arrive at instrumental variable estimates of the effect of collective action . We estimate the following first stage:

$$distancetoriver_{ct} = \gamma_c + r_t + treated_{ct} + \nu_{ct} \tag{4}$$

$distancetoriver_{ct}$ is the distance in meters to the nearest river for grid cell c in period t. γ_c is a vector of grid cell fixed effects. r_t is a vector of period fixed effects. $treated_{ct}$ is an indicator equal to one if grid cell c was on a river in period $t-1$ and is no longer on a river. ν_{ct} is a standard error clustered at the grid cell level.

We use the predicted values from the first stage in the following second stage, and estimate the system using two stage least squares:

$$Y_{ct} = \gamma_c + r_t + distancetoriver_{ct} + \varepsilon_{ct} \tag{5}$$

Where Y_{ct} is an outcome of interest, $distancetoriver_{ct}$ is the distance in meters to the nearest river for grid cell c in period t predicted in the first stage. We include unit and period fixed effects (γ_c and r_t), and ε_{ct} is a standard error clustered at the grid cell level.

This modeling setup captures the following intuition: what happens to those grid cells that were inhabited if the pressure of collective action goes up as a result of a river shift?

Table 10 column (1) studies settlement and column (2) studies public good provision. Panel I provides estimates of equation 5, the second stage. Panel II provides estimates of equation 4, the first stage. Panel III provides reduced form estimates, which are estimates of equation 4 substituting the endogenous variable for the outcome variables in columns (1) and (2).

Column (1), panel I, shows that, on average, settlement density falls when we shock collective action pressure upwards. Column (1), panel II establishes that indeed a river shift away does shock collective action pressure upwards. The first stage F-statistics are large enough to provide confidence in the strength of the instrument, but not so large as to raise suspicion of a mechanical first stage relationship. As before, we see canals being built in response to an increase in collective action pressure. This result is in column (2), panel I. Increasing the distance to the nearest river by one-kilometer increases the probability of being on a canal with about four percentage points. The reduced form estimates in panel III are in line with the second stage results in panel I.

This section has provided evidence for the last part in the causal chain of our hypothesis: river shifts induce a collective action problem and a demand for state institutions or a 'social contract'. The state provides public goods that offset the adverse effects of the river shift.

7 The collapse of settlement in the center of the plain

After the Islamic conquest of 653 CE the system of taxation, state institutions, and public good provision we have studied so far collapsed. We document in our atlas that this process started around 900CE. From then on, the state no longer respond to the demand for public good provision, irrigation collapsed, and ultimately settlement collapsed back to the level it had been several thousand years earlier. This collapse has persisted essentially to today. For example, Figure 13 maps settlement in the sample area in 1911. All settlement has returned to the rivers, leaving the most productive parts of the plain unfarmed. This collapse is an important challenge to our hypothesis because clearly Iraqis still stood to gain from public good provision. Why did this collapse happen?

In this section, we first show that the collapse is concentrated where collective action pressure is higher. We then show, using newly collected data on political institutions, that the Islamic conquest led to a deterioration of the stability of government. We finally summarize the consensus among historians on the collapse. We find that the Islamic conquest broke the social contract from the side of the government by relying on outside finance and military recruitment. No longer in need of local taxes, rulers had no incentive to provide public goods.

We first study the incidence of the collapse, taking its occurrence as given. No river shifts happened in the centuries after the Islamic conquest, so we can not rely on the identification strategy of this paper to test for a causal effect of collective action on this collapse. Instead, we re-estimate equation 2, the panel fixed effects specification, omitting the treatment indicator since no river shift occurred. We report the coefficients on the period fixed effects. We median split the sample by proximity to the nearest river. In Figure 14, we plot the results from this exercise. Although there is a general drop in settlement, this drop is concentrated in parts of the sample area where collective action pressure is higher.

Although these results support the idea that the capacity of the state was associated with the collapse, they do not speak to the question what changed from before the Islamic conquest to after. We now provide evidence that the Islamic conquest led to a change in political institutions towards despotism and a break in the social contract. To do so, we follow Blaydes and Chaney (2013), who show that the shorter duration of a ruler's tenure in a century is associated with more despotic rule. Despotism was associated with a constant tournament among warlords to be the ruler. Once ruling, these warlords would expropriate as much as possible, anticipating to be overthrown. This argument is the rationale behind shorter duration of leader tenure, in the Islamic world, being a measure of a more despotic state. More broadly ruler tenure duration can be interpreted as a measure of political stability. We code the tenure of each ruler in our sample area from about 3000BCE until the first world war, and compute the average tenure by century.[19] Figure 15 shows a marked drop in average tenure, and therefore an increase in despotism and a loss of political stability, at the time of the Islamic conquest.[20]

The debate among historians on this collapse mostly centers around whether development after the Islamic conquest is associated with Muslim doctrine, or with the institutions Muslim conquerors brought. Chaney (2019) summarizes the evidence and concludes that the institutional organization of tribal society, rather than Islamic doctrine, is the more plausible explanation. The Muslim conquerors of southern Iraq relied on slave armies (the 'Mamluks'), financed with income from taxes, but also with income from outside our sample area since Muslim rulers controlled a much larger area than just our sample area. The reliance on external finance and slave soldier disconnected rulers from the social contract in which taxes (in kind and in labor in the form of conscription) were exchanged for public goods. The rulers relied less on local taxation, and did not need to provide public goods at the same level. While we can not make causal statements on the collapse, the balance of the historical evidence suggests that the Islamic conquest changed institutions, and disconnected the population from the ruling elite. This led to underinvestment in irrigation infrastructure, and the collapse of settlement and economic activity (Chaney, 2019; Blaydes and Chaney, 2013). We wrote a supporting paper that further studies the historical sources and data available for the Islamic period for southern Iraq in particular. We conclude that the collapse of society was preceded by a collapse in tax collection which, in turn, resulted from repeated tournaments among successive rulers, who often looted the irrigation treasury in the process (Allen and Heldring, 2018).

Taken together, this section provides evidence for the claim that the Islamic conquest changed the incentives for the rulers to engage in their side of the social contract. This led to the collapse of public good provision. More broadly, therefore, this collapse is an example of politicians sacrificing longer term economic activity and surplus for short term political gain (Acemoglu and Robinson, 2000).

[19] We fully describe the data and the coding procedure in the data appendix.

[20] A t-test shows that the drop is significant when comparing the five centuries after the conquest to either the five centuries before, a millennium before, or the entire time-series before.

8 Conclusion

In this paper, we study institutional adaptation to environmental change. We test the hypothesis that changes in the environment create a collective action problem. This collective action problem creates demand for states. These states solve the collective action problem by providing public goods that offset the environmental change. This hypothesis is closely related to Hobbes' idea of a social contract, and complements 'supply' side theories of state formation that center on expropriation.

To test this hypothesis, we constructed a panel of environmental change, settlement, state formation, and public good provision for southern Iraq that covers all of modern human history, from 5000BCE until the present. Within this panel, we estimate a simple panel difference-in-differences model restricted to areas close to moving rivers, comparing those places that are on a river before and after a river shift, to those that are equidistant from a river.

Within this empirical setup we provide evidence for each step in the causal logic of our hypothesis: In response to a river shift: 1) settlement falls. 2) states form. 3) these states provide irrigation canals that allow the population to farm areas that were formerly irrigated by a river. 4) places with higher collective action pressure see more public goods provided.

Our paper delivers a 'positive' message about environmental change. In response to sudden changes in the environment, Iraqis founded the first city states, states and empires. This adaptation enabled southern Iraq to become the cradle of civilization and sustain large populations in what is essentially an arid desert. We also provide evidence for a 'demand side' theory of state formation, where individuals willingly give up resources and autonomy in exchange for public good provision.

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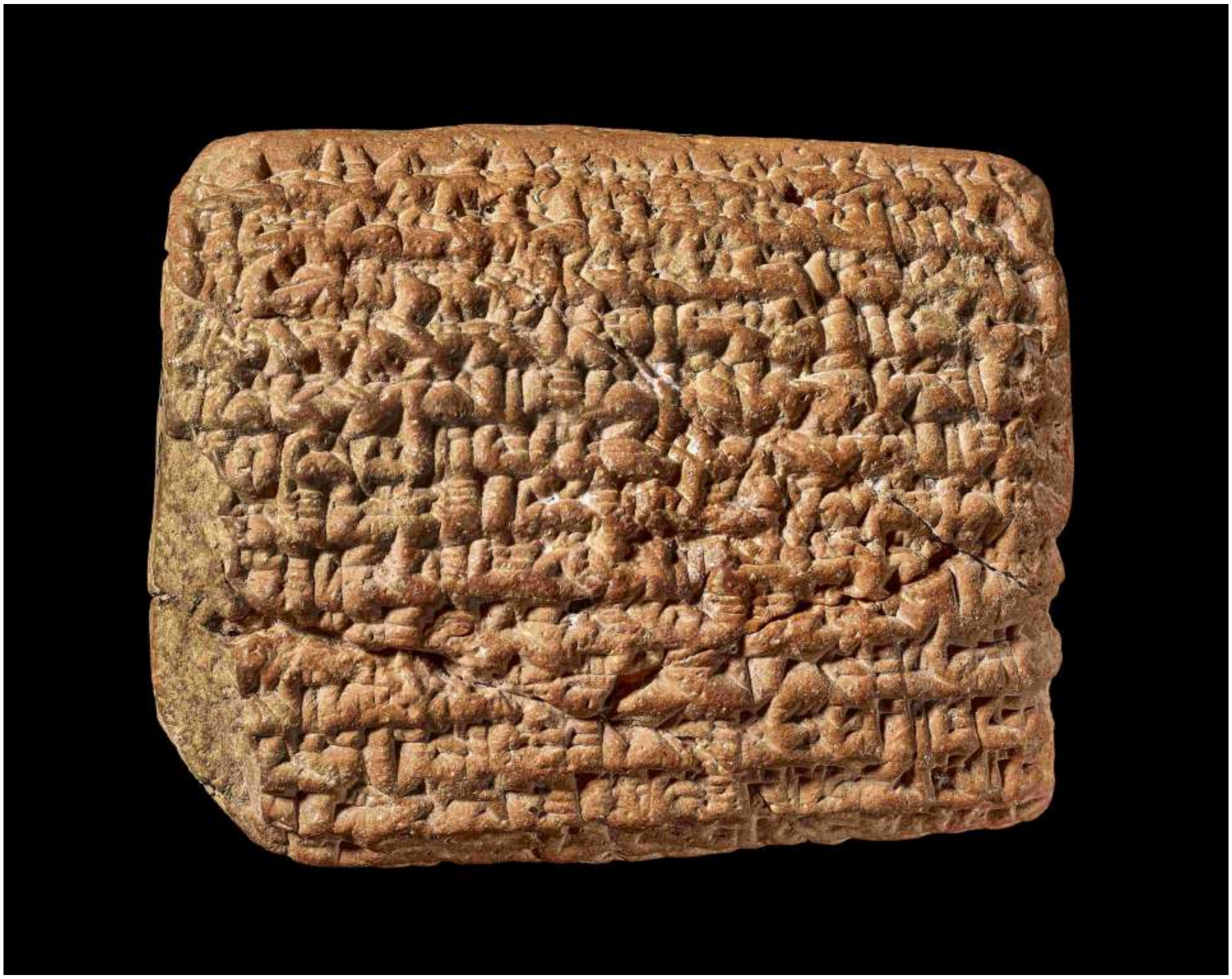
Figure 1: A CONTRACT DETAILING TAX PAYMENTS IN EXCHANGE FOR PUBLIC PROVISION



Notes: This tablet is an example of a social contract, exchanging taxes for maintenance of public goods. It is dated to the first year of the reign of Amīl-Marduk, who died around 560BCE. The translation reads:

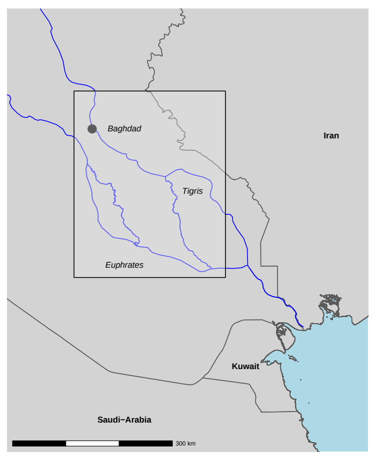
"The gugallu-office for the Borsippa-canal, which is in the gift (bīt qīpti) of Nabû-nādin-šumi, the governor of Borsippa, the son of Mušēzib-Marduk of the Ibnāya family, for the land from the Harru-ša-Bīt-Bēlāya until the border of the estate of Bēl-ēter, son of Ahu-iddin, is at the disposal of Nergal-uballit, son of Nādin of the Hattuērеš family, for yearly two minas of silver. Every year, Nergal-uballit will pay to Nabû-nādinšumi, the governor of Borsippa, (these) two minas of silver for the gugallu-office. The sheep (to be delivered) by the village headmen (hazan āli) [and ...] he shall deliver in the presence of Širiktu. He shall clothe him with a [...-]...-garment (?). He shall collect [x] measures (mašīhu) of dates for each kurru of land at the expense of the fifty-collective (ina muhhi hanšê) (and) two measures of barley. He guarantees for guarding the canal and taking care (hâru) of the royal road. This is in addition to earlier debt-notes of Nabû-nādin-šumi against Nergal-uballit which he might produce for the purpose of settling accounts. (Witnesses, scribe). Bīt-Ina-tēšî-ēter on the Borsippa-canal. 16.7.1 Amīl-Marduk, king of Babylon. He shall pay the silver in monthly installments. The garlic, flax and sesame belong to the governor in addition (to the rest).""

The translation is in Jursa and Waerzeggers (2009, p. 242). The tablet is held by the British Museum under catalog number BM 28933. Photograph copyright: The Trustees of the British Museum.

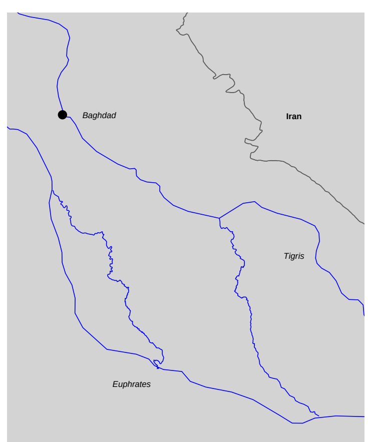
Figure 2: SAMPLE AREA

(a) The Middle-East

(b) Southern Iraq



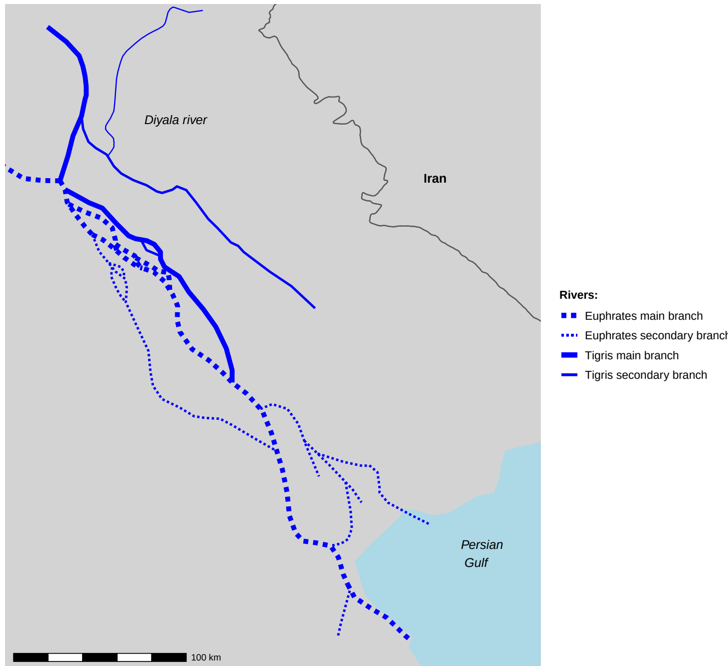
(c) The sample area



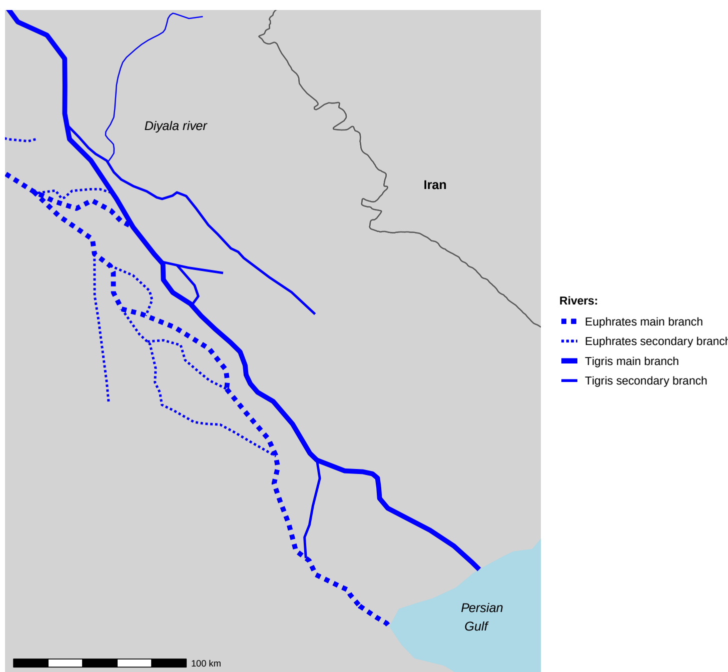
Notes: Subfigure (a) depicts the Middle-East using current country borders. The bounding box in (a) is the full extent of (b). Subfigure (b) also maps Baghdad and the current flow of the Euphrates and Tigris rivers. The bounding box in (b) is the extent of (c). All further maps in this paper are zoomed in to the extent of (c). We do not extend the sample area to the current Persian Gulf since historically the Persian gulf reached the southern part of our sample area. The 'Atlas of Long-run Development in Iraq' that is enclosed with this paper shows the fluctuating coastline over time.

Figure 3: EXAMPLE OF A RIVER SHIFT: 1800BCE

(a) River network, 1900BCE

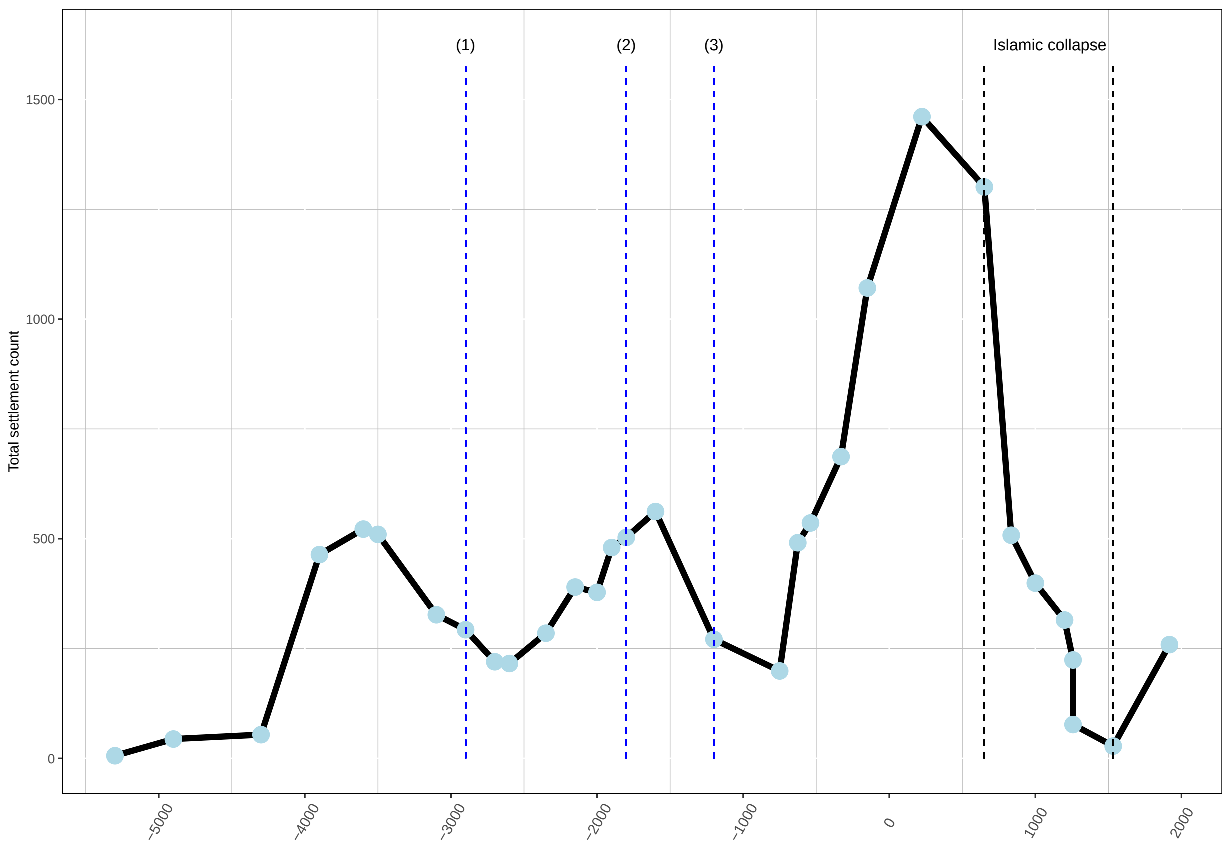


(b) River network, 1800BCE



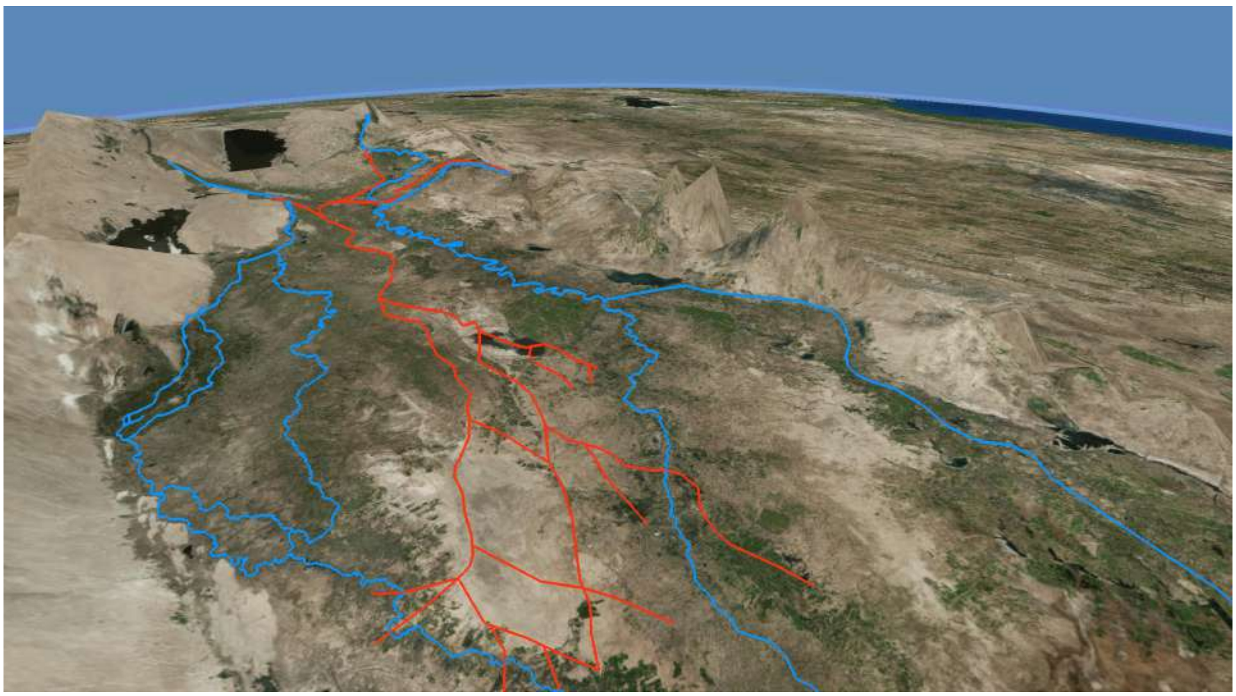
Notes: Subfigure (a) depicts the river network in our sample area before a river shift that took place around 1800BCE. Subfigure (b) maps the river network after the move. The data sources for our reconstructions of such moves as well as a catalog with maps and descriptions of each move is in the appendix.

Figure 4: SETTLEMENT VARIES OVER TIME



Notes: This figure shows the total number of settlements over time. Blue dots indicate archeological periods, which form the time-series dimensions of our panel. These are described fully in the data appendix. Vertical numbered lines indicate the timing of our three time-series experiments. Line (1) indicates the city states experiment. Line (2) indicates the centralized states experiment. Line (3) indicates the placebo experiment. The range indicated by Islamic collapse bounds the collapse in settlement that occurred after the Islamic conquest. We study this collapse in section 6.

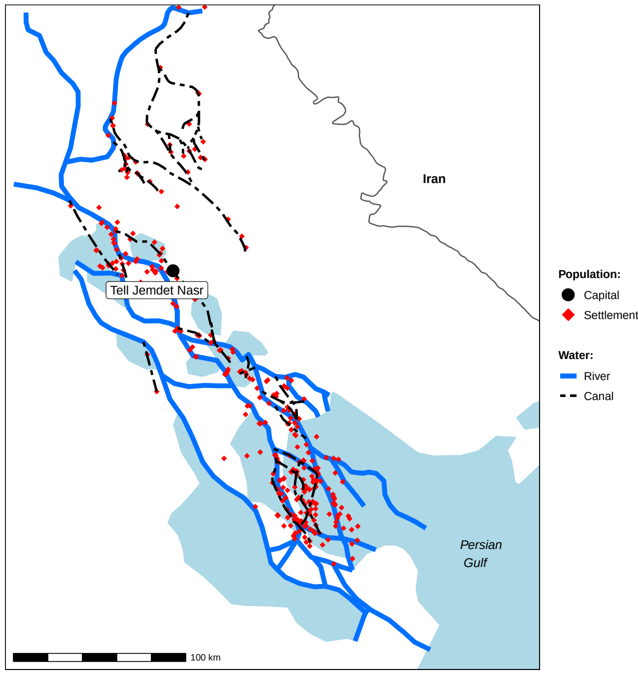
Figure 5: THE POSITION OF RIVERS IN OUR SAMPLE AREA, 5000BCE AND TODAY



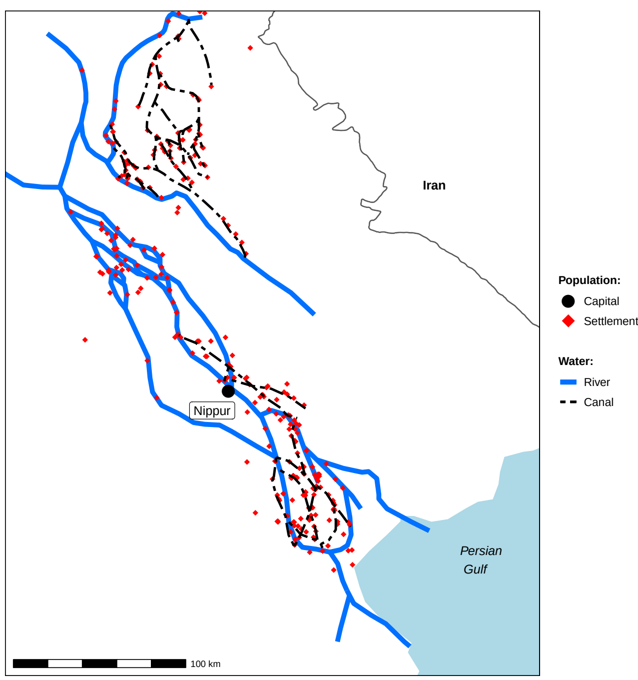
Notes: This map shows a three dimensional rendering of the northern part of the study area of this paper. We did not render the mountains beyond the immediate boundaries of the sample area. In red (darker grey) we indicate the river system around 5000BCE in the center of the plain and in blue (lighter grey) we indicate the river system today.

Figure 6: RIVER NETWORK, SETTLEMENT AND CANALS BEFORE AND AFTER THE CITY STATES EXPERIMENT

(a) Before the river shift



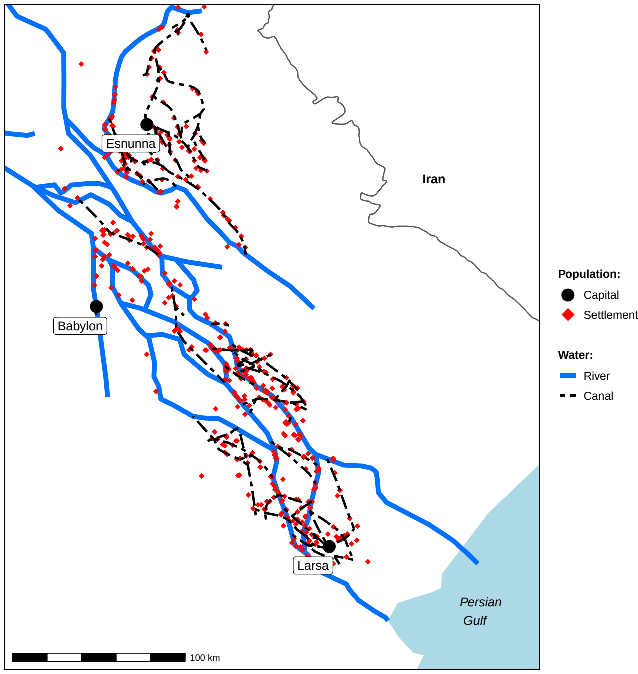
(b) After the river shift



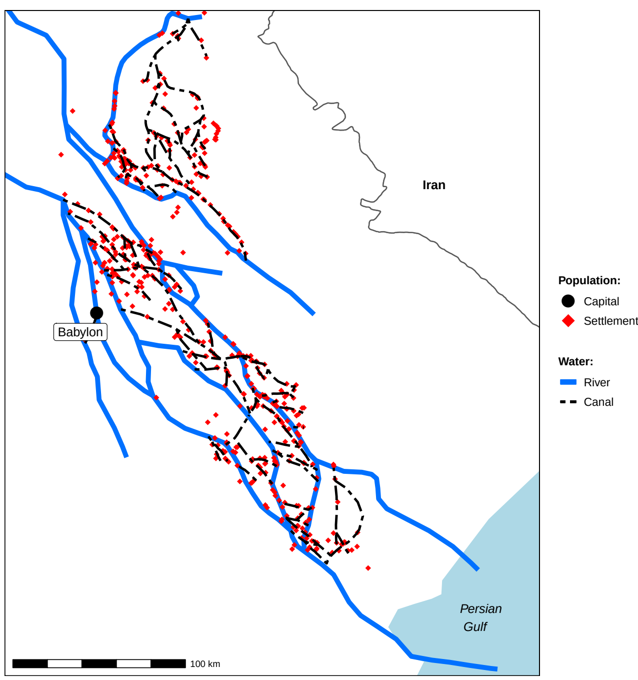
Notes: Subfigure (a) depicts the river network, settlement and canals in our sample area in period 7, the Early Dynastic I period, which constitutes our city states experiment. Subfigure (b) maps river network, settlement and canals after the river shift. The data sources for our reconstructions of such moves as well as a catalog with maps and descriptions of each move is in the appendix.

Figure 7: River network, settlement and canals before and after the centralized states experiment

(a) Before the river shift



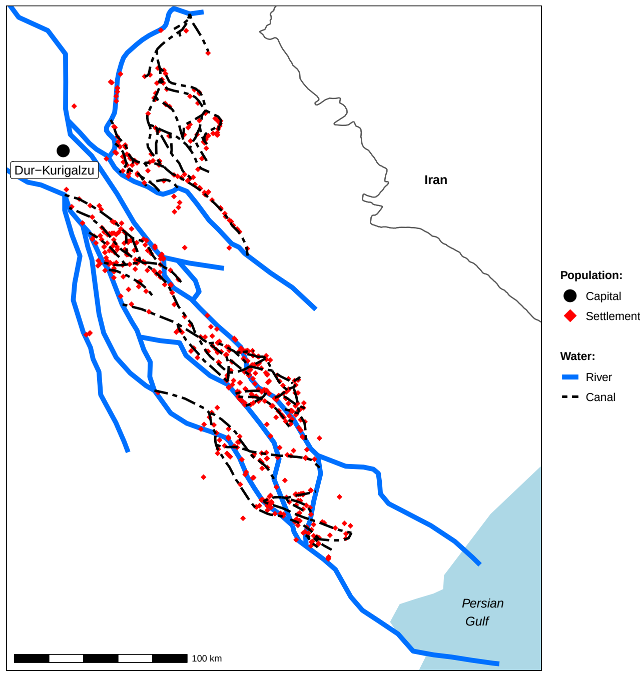
(b) After the river shift



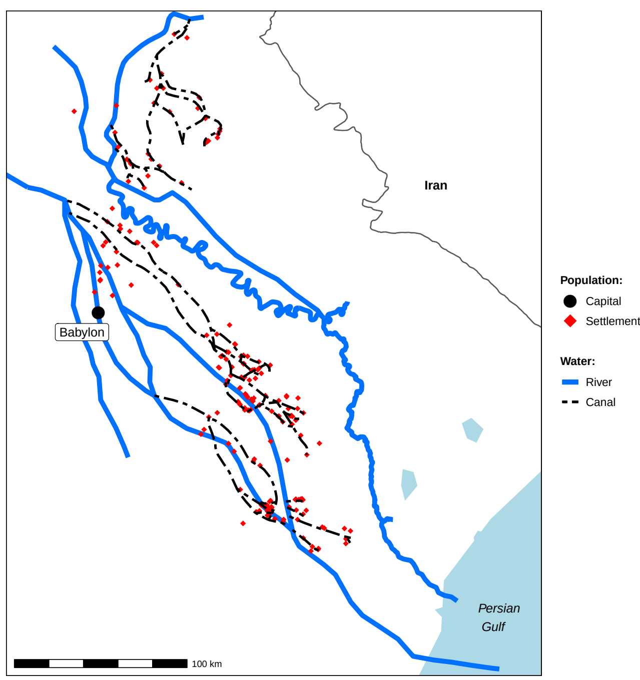
Notes: Subfigure (a) depicts the river network, settlement and canals in our sample area before period 15, the Old-Babylonian period, which constitutes our centralized states experiment. Subfigure (b) maps river network, settlement and canals after the river shift. The data sources for our reconstructions of such moves as well as a catalog with maps and descriptions of each move is in the appendix.

Figure 8: RIVER NETWORK, SETTLEMENT AND CANALS BEFORE AND AFTER THE PLACEBO EXPERIMENT

(a) Before the river shift

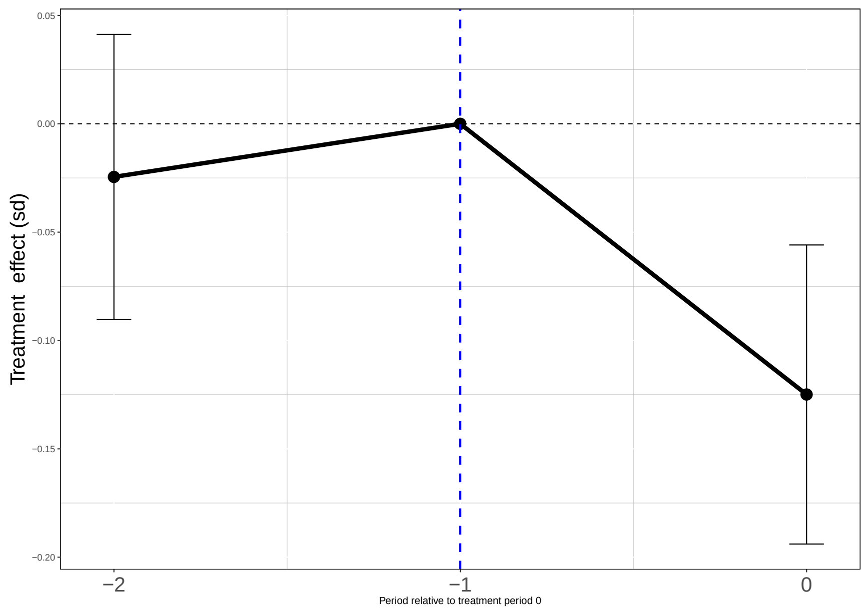


(b) After the river shift



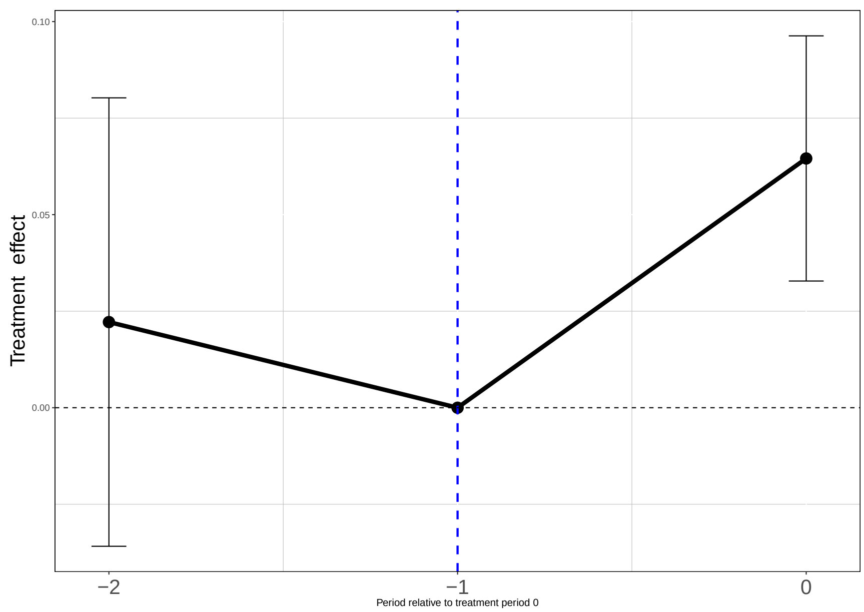
Notes: Subfigure (a) depicts the river network, settlement and canals in our sample area before period 17, the Middle-Babylonian period, which constitutes our placebo experiment. Subfigure (b) maps river network, settlement and canals after the river shift. The data sources for our reconstructions of such moves as well as a catalog with maps and descriptions of each move is in the appendix.

Figure 9: A RIVER SHIFT NEGATIVELY AFFECTS SETTLEMENT OVER THE ENTIRE PANEL



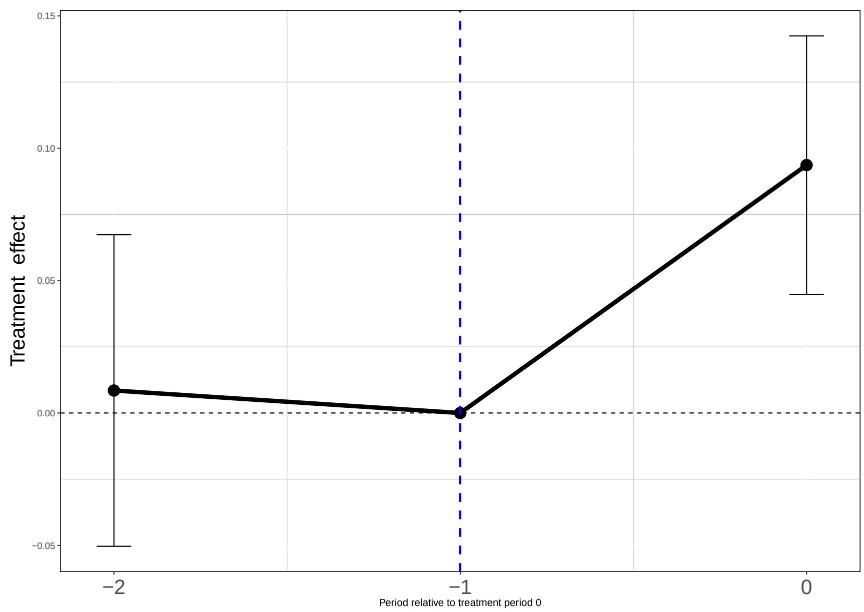
Notes: This graph plots point estimates and confidence estimated from equation 3. The outcome variable in this regression is the number of settlements in grid cell c at time t. The corresponding regression is in column (1) of Table 5. The point estimate for period -2 shows that there are no systematic pre-trends in settlement that affect the causal interpretation of the point estimate for period 0. The point estimate for period 0 shows that on average over the entire panel a move in the river away from a location results in a reduction in settlement.

Figure 10: A RIVER SHIFT LEADS TO STATE FORMATION, CITY STATES PERIOD



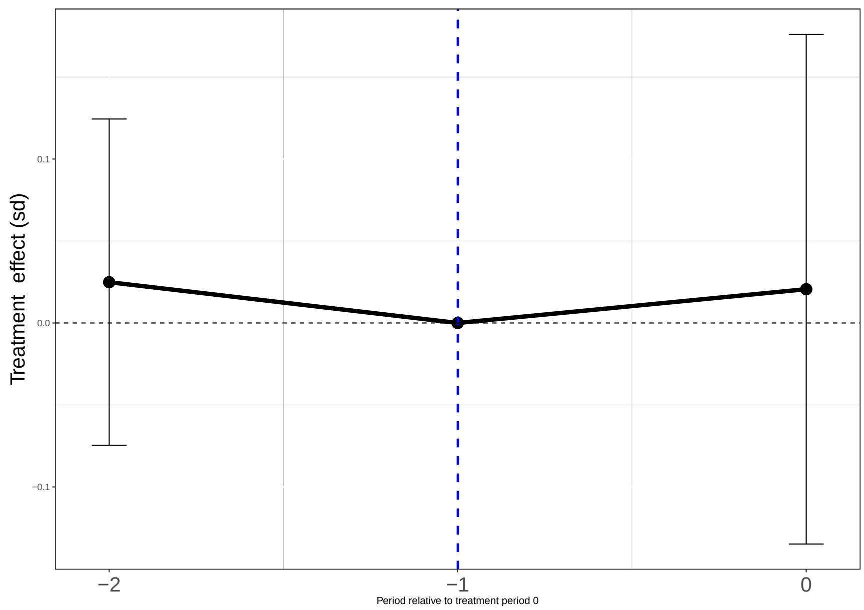
Notes: This graph plots point estimates and confidence estimated from equation 3. The outcome variable in this regression is an indicator equal to one if a grid cell was part of a city in our city states period. The corresponding regression is in column (1) of Table 6. The point estimate for period -2 shows that there are no systematic pre-trends in city state formation that affect the causal interpretation of the point estimate for period 0. The point estimate for period 0 shows that on average over the entire panel a move in the river away from a location results in state formation.

Figure 11: A RIVER SHIFT LEADS TO PUBLIC GOOD PROVISION



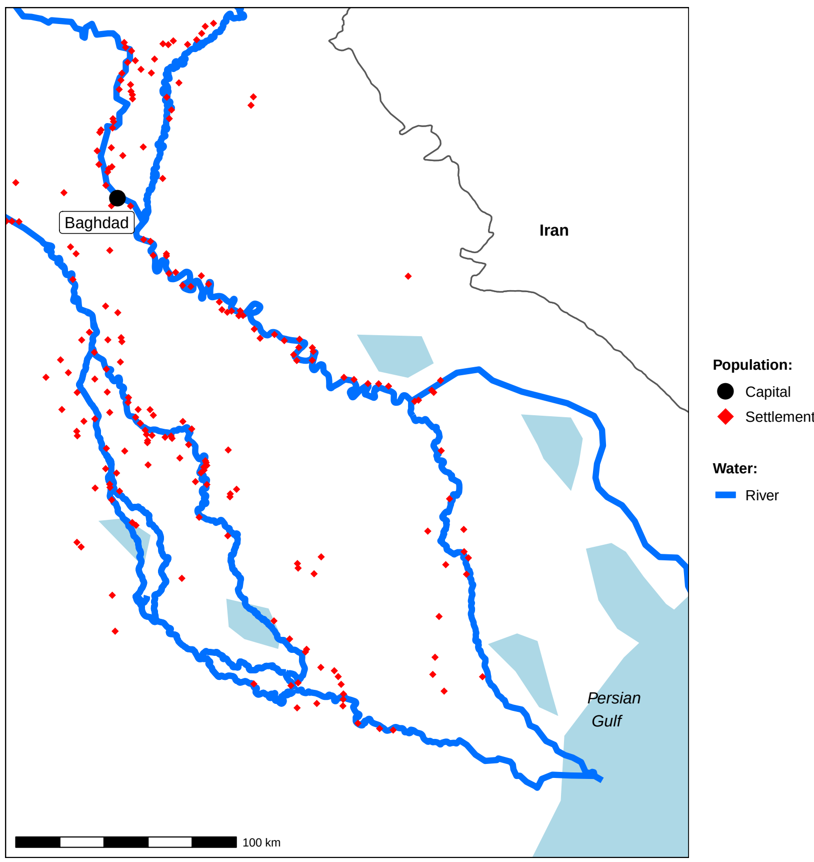
Notes: This graph plots point estimates and confidence estimated from equation 3. The outcome variable in this regression is an indicator equal to one if a grid cell was within 5 kilometers from a canal in the city states period. The corresponding regression is in column (1) of Table 8. The point estimate for period -2 shows that there are no systematic pre-trends in public good provision that affect the causal interpretation of the point estimate for period 0. The point estimate for period 0 shows that on average over the entire panel a move in the river away from a location results in canal building to that grid cell.

Figure 12: WHEN PUBLIC GOODS ARE PROVIDED, A RIVER SHIFT NO LONGER AFFECTS SETTLEMENT



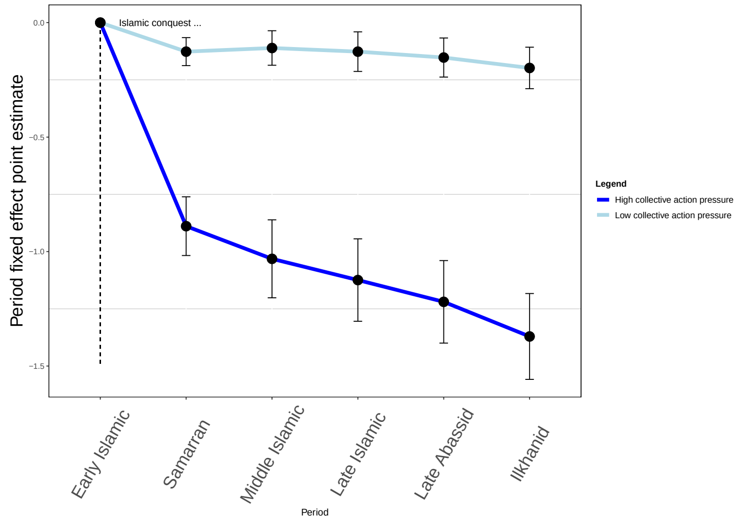
Notes: This graph plots point estimates and confidence estimated from equation 3. The outcome variable in this regression is the number of settlements in grid cell c in our centralized state experiment. The corresponding regression is in column (2) of Table 9. The point estimate for period -2 shows that there are no systematic pre-trends in settlement that affect the causal interpretation of the point estimate for period 0. The point estimate for period 0 shows that on average settlement does not fall when there is a centralized state.

Figure 13: SETTLEMENT IN 1911 RETURNS TO RIVERS



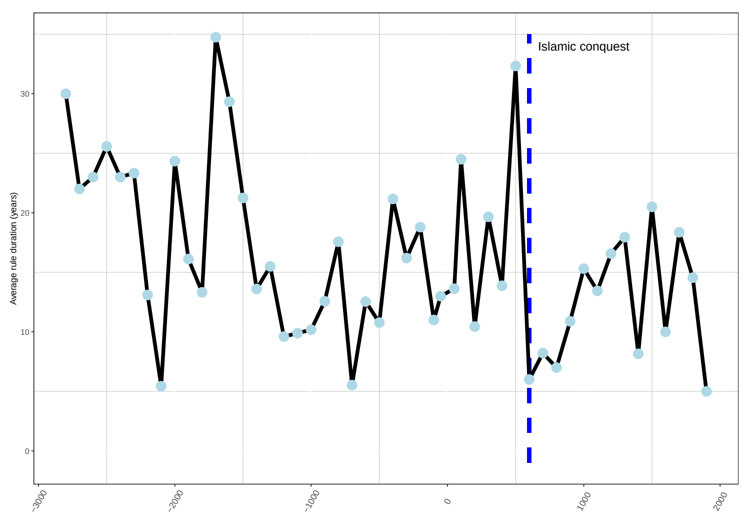
Notes: this map depicts the river network and settlement in 1911.

Figure 14: THE ISLAMIC COLLAPSE IS CONCENTRATED AWAY FROM RIVERS



Notes: This graph plots point estimates and confidence estimated from equation 2. The outcome variable in this regression is the number of settlements in a grid cell. We report two sets of point estimates and confidence intervals. 'High collective action pressure' grid cells are those further away from rivers (above the median distance) and 'low collective action pressure' grid cells are those close to the river.

Figure 15: THE ISLAMIC CONQUEST SHARPLY REDUCES POLITICAL STABILITY



Notes: This graph plots a time series of the average length (in years) of tenure of rulers in our sample area. We describe the data, and data collection procedure, in the appendix.

Table 1: HISTORICAL RIVER SHIFTS

	Timing	Time series period	Experiment	Inclusion or exclusion notes	Atlas figure
1	Between 5000BCE and 4200BCE	4	No	Can not date shift precisely	Figure 2
2	Between 4000BCE and 3500BCE	6	No	No river shift, but minor branch becomes main branch	Figure 3
3	Around 2900BCE	8	Yes	This is our 'city states experiment'	Figure 4
4	Between 2700BCE and 2500BCE	9	No	Limited data availability (see table 2 in the data appendix)	Figure 5
5	1800BCE	15	Yes	This is our 'centralized states experiment'	Figure 6
6	Between 1200BCE and 1000BCE	17	Yes	This is our 'placebo experiment'	Figure 7
7	Around 700BCE	19	No	Limited data availability (see table 2 in the data appendix)	Figure 8
8	Between 0CE and 500CE	23	No	Negligible shift	Figure 9
9	Between 500CE and 1000CE	26	No	River shift is outside the coverage of our archeological surveys	Figure 10
10	Around 1850	31	No	River shift is outside the coverage of our archeological surveys	Figure 11

Notes: This table gives a concise overview of the river shifts that form the basis of the identification strategy of this study. The column labeled timing indicates the timing of each shift. Period number is the time-series period we assigned the river shift to. For shifts that have a wider timing window, we assign the shift to the period by which we know the shift to have happened with certainty. The column labeled experiment contains an indicator for whether we separately study this river shift in the paper. Inclusion or exclusion notes provides a brief rationale for inclusion or exclusion of a river shift as an experiment. Atlas figure contains a reference to the figure in our atlas that maps the river shift. Each river shift is described in detail in the data appendix.

Table 2: SUMMARY STATISTICS

	mean	sd	min	max
River shift (yes/no)	0.02	0.14	0.00	1.00
Nr. of settlements	0.32	1.04	0.00	26.00
Average rainfall (mm)	11.77	2.39	8.08	18.92
Average temperature (C)	23.15	0.38	22.58	24.02
Barley suitability (rainfed)	578.98	658.03	0.00	2615.00
Barley suitability (irrigated)	3927.11	147.16	3590.00	4083.00
Under city state (yes/no)	0.27	0.44	0.00	1.00
Nr. of admin buildings in capital nearest city	0.56	1.07	0.00	5.00
Admin building area nearest city (m2)	11955.72	30206.23	0.00	283800.00
Distance to nearest capital (m)	113952.66	79854.01	298.68	442054.63
Nr. of admin buildings in capital	1.50	1.32	0.00	4.00
Admin building area capital city (m2)	36535.13	61561.04	0.00	283800.00
On canal (yes/no)	0.29	0.45	0.00	1.00
Average duration ruler tenure in nearest city (years)	13.63	4.36	3.51	35.00
Observations	41075			

Table 3: THE EFFECT OF A RIVER SHIFT ON GEOGRAPHICAL FEATURES (CROSS-SECTION)

Dependent variable:	Rainfall (1)	Temperature (2)	Barley Suitability Rainfed (3)	Barley Suitability Irrigated (3)
River shift any distance (yes/no)	-14.84***	15.95***	-13.86***	5.777***
	(0.504)	(0.510)	(0.533)	(0.569)
	[3.754]	[3.399]	[3.636]	[2.733]
Mean dep. var.	11.77	23.15	579.0	3927.1
Observations	1325	1325	1325	1325
R^2	0.343	0.396	0.299	0.0519

Notes: All regressions are estimated using OLS. All estimated coefficients are standardized. The cross-sectional unit of observation is a 5x5 kilometer grid cell. The time-series period is an archeological period (see data appendix). Rainfall is rainfall in millimeters averaged over a grid cell. Temperature is the average temperature in a grid cell. Barley suitability (rainfed) the suitability of the soil for growing rainfed barley. Barley suitability (irrigated) the suitability of the soil for growing barley when irrigating the land. River shift any distance (yes/no) is an indicator equal to one if the distance to the nearest river in period t-1 is different from the distance to the nearest river in period t. Heteroskedasticity robust standard errors are in parentheses. Conley (1999) standard errors are in square brackets. * indicates significance at the 10 percent level, ** at the 5 percent level, *** at the 1 percent level.

Table 4: THE EFFECT OF A RIVER SHIFT ON LAGGED SETTLEMENT

Dependent variable:	Nr. of settlements lag 1 (1)	Nr. of settlements lag 2 (2)	On canal (yes/no) lag 1 (3)	On canal (yes/no) lag 2 (4)
River move (yes/no)	-0.00337	0.00443	-0.00432	-0.000785
	(0.00439)	(0.00510)	(0.00447)	(0.00468)
	[0.0063]	[0.0067]	[0.0091]	[0.0101]
Mean dep. var.	34909	33584	34909	33584
Observations	0.33	0.33	0.51	0.52
Clusters	1325	1325	1325	1325

Notes: All regressions are estimated using OLS. All estimated coefficients are standardized. The cross-sectional unit of observation is a 5x5 kilometer grid cell. The time-series period is an archeological period (see data appendix). Nr. of settlements is the count of settlements. River shift (yes/no) is an indicator equal to one if the nearest river was within 5 kilometers in period t-1 the previous period and is further than 5 kilometers away in period t. All regressions include period and grid cell fixed effects. Heteroskedasticity robust standard errors clustered at the grid cell level are in parentheses. Conley (1999) standard errors are in square brackets. * indicates significance at the 10 percent level, ** at the 5 percent level, *** at the 1 percent level.

Table 5: THE EFFECT OF A RIVER SHIFT ON SETTLEMENT

Dependent variable:	Nr. of settlements		
Sample:	*Full sample*	*High environmental pressure*	*Low environmental pressure*
	(1)	(2)	(3)
River shift (yes/no)	-0.124***	-0.133***	0.0948
	(0.0336)	(0.0343)	(0.192)
	[0.0619]	[0.0633]	[0.2709]
Period x archeological excavation	Y	Y	Y
Period x rainfall	Y	Y	Y
Period x temperature	Y	Y	Y
P-value pre-trend	0.54	0.44	0.31
Observations	72042	52425	18951
Clusters	994	739	246
R^2	0.26	0.26	0.22

Notes: All regressions are estimated using OLS. All estimated coefficients are standardized. The cross-sectional unit of observation is a 5x5 kilometer grid cell. The time-series period is an archeological period (see data appendix). Nr. of settlements is the count of settlements. River shift (yes/no) is an indicator equal to one if the nearest river was within 5 kilometers in period t-1 the previous period and is further than 5 kilometers away in period t. Period x archeological excavation is a vector of period-relative-to-treatment fixed effects interacted with indicators for each of the three main archeological surveys of settlement we use. These surveys are described and mapped in the data appendix. Period x rainfall is a vector of period-relative-to-treatment fixed effects interacted with average rainfall. Period x temperature is a vector of period-relative-to-treatment fixed effects interacted with average rainfall. All regressions include period and grid cell fixed effects. Heteroskedasticity robust standard errors clustered at the grid cell level are in parentheses. Conley (1999) standard errors are in square brackets. * indicates significance at the 10 percent level, ** at the 5 percent level, *** at the 1 percent level.

Table 6: THE EFFECT OF A RIVER SHIFT ON STATE FORMATION: CITY STATES

Dependent variable:	Under city state (yes/no)	Nr. of admin buildings nearest city	Admin building area nearest city (m2)
	(1)	(2)	(3)
River shift (yes/no)	0.0646***	0.0787***	387.5***
	(0.0162)	(0.0234)	(132.1)
	[0.0293]	[0.0413]	[191.2]
Period x archeological excavation	Y	Y	Y
Period x rainfall	Y	Y	Y
Period x temperature	Y	Y	Y
P-value pre-trend	0.45	0.52	0.90
Mean dep. var.	0.13	0.24	911.45
Observations	2559	2559	2559
Clusters	853	853	853
R^2	0.74	0.87	0.87

Notes: All regressions are estimated using OLS. The cross-sectional unit of observation is a 5x5 kilometer grid cell. The time-series period is an archeological period (see data appendix). Under city state (yes/no) is an indicator equal to one if the nearest city has at least one administrative building. Nr. of admin buildings nearest city is the sum of the number of palaces and the number of ziggurats in the nearest city. Admin building area nearest city (m2) is the total area in square meters of all palaces and ziggurats in the capital city that governs the nearest city. River shift (yes/no) is an indicator equal to one if the nearest river was within 5 kilometers in period t-1 the previous period and is further than 5 kilometers away in period t. Period x archeological excavation is a vector of period-relative-to-treatment fixed effects interacted with indicators for each of the three main archeological surveys of settlement we use. These surveys are described and mapped in the data appendix. Period x rainfall is a vector of period-relative-to-treatment fixed effects interacted with average rainfall. Period x temperature is a vector of period-relative-to-treatment fixed effects interacted with average rainfall. All regressions include period and grid cell fixed effects. Heteroskedasticity robust standard errors clustered at the grid cell level are in parentheses. Conley (1999) standard errors are in square brackets. * indicates significance at the 10 percent level, ** at the 5 percent level, *** at the 1 percent level.

Table 7: THE EFFECT OF A RIVER SHIFT ON STATE FORMATION: CENTRALIZED STATES

Dependent variable:	Distance to nearest capital (m)	Nr. of admin buildings capital city	Admin building area capital city (m2)
	(1)	(2)	(3)
River shift (yes/no)	-14919.1***	0.247***	825.9***
	(3473.3)	(0.0430)	(121.0)
	[6042.5]	[0.0987]	[304.9]
Period x archeological excavation	Y	Y	Y
Period x rainfall	Y	Y	Y
Period x temperature	Y	Y	Y
P-value pre-trend	0.83	0.20	0.03
Mean dep. var.	61692.79	1.35	22579.15
Observations	2829	2829	2829
Clusters	943	943	943
R^2	0.91	0.90	0.99

Notes: All regressions are estimated using OLS. The cross-sectional unit of observation is a 5x5 kilometer grid cell. The time-series period is an archeological period (see data appendix). Distance to nearest capital (m) is the distance to the nearest capital city in meters. A capital city is a city that dominates at least one other city (see the data appendix). Distance is measured from a grid cell's centroid. Nr. of admin buildings in capital is the sum of the number of palaces and the number of ziggurats in the capital city that governs the nearest city. Admin building area capital city (m2) is the total area in square meters of all palaces and ziggurats in the nearest city. River shift (yes/no) is an indicator equal to one if the nearest river was within 5 kilometers in period t-1 the previous period and is further than 5 kilometers away in period t. Period x archeological excavation is a vector of period-relative-to-treatment fixed effects interacted with indicators for each of the three main archeological surveys of settlement we use. These surveys are described and mapped in the data appendix. Period x rainfall is a vector of period-relative-to-treatment fixed effects interacted with average rainfall. Period x temperature is a vector of period-relative-to-treatment fixed effects interacted with average rainfall. All regressions include period and grid cell fixed effects. Heteroskedasticity robust standard errors clustered at the grid cell level are in parentheses. Conley (1999) standard errors are in square brackets. * indicates significance at the 10 percent level, ** at the 5 percent level, *** at the 1 percent level.

Table 8: THE EFFECT OF A RIVER SHIFT ON PUBLIC GOOD PROVISION

Dependent variable:	On canal (yes/no)		
Periods in sample:	*City States*	*Centralized State*	*Invasion*
	(1)	(2)	(3)
River shift (yes/no)	0.0936***	0.282***	0.0710
	(0.0249)	(0.0578)	(0.0646)
	[0.0355]	[0.0839]	[0.0936]
Period x archeological excavation	Y	Y	Y
Period x rainfall	Y	Y	Y
Period x temperature	Y	Y	Y
P-value pre-trend	0.78	0.73	0.10
Mean dep. var.	0.31	0.43	0.52
Observations	2559	2829	1899
Clusters	853	943	633
R^2	0.87	0.88	0.77

Notes: All regressions are estimated using OLS. The cross-sectional unit of observation is a 5x5 kilometer grid cell. The time-series period is an archeological period (see data appendix). On canal (yes/no) is an indicator variable equal to one if a canal crosses a grid cell. River shift (yes/no) is an indicator equal to one if the nearest river was within 5 kilometers in period t-1 the previous period and is further than 5 kilometers away in period t. Period x archeological excavation is a vector of period-relative-to-treatment fixed effects interacted with indicators for each of the three main archeological surveys of settlement we use. These surveys are described and mapped in the data appendix. Period x rainfall is a vector of period-relative-to-treatment fixed effects interacted with average rainfall. Period x temperature is a vector of period-relative-to-treatment fixed effects interacted with average rainfall. All regressions include period and grid cell fixed effects. Heteroskedasticity robust standard errors clustered at the grid cell level are in parentheses. Conley (1999) standard errors are in square brackets. * indicates significance at the 10 percent level, ** at the 5 percent level, *** at the 1 percent level.

Table 9: THE EFFECT OF A RIVER SHIFT ON SETTLEMENT

Dependent variable:	Nr. of settlements		
Periods in sample:	*City States*	*Centralized State*	*Invasion*
	(1)	(2)	(3)
River shift (yes/no)	0.107*	0.0206	-0.287***
	(0.0553)	(0.0792)	(0.0897)
	[0.1093]	[0.0448]	[0.0837]
Period x archeological excavation	Y	Y	Y
Period x rainfall	Y	Y	Y
Period x temperature	Y	Y	Y
P-value pre-trend	0.90	0.62	0.34
Observations	2559	2829	2541
Clusters	853	943	847
R^2	0.75	0.82	0.70

Notes: All regressions are estimated using OLS. The cross-sectional unit of observation is a 5x5 kilometer grid cell. The time-series period is an archeological period (see data appendix). Nr. of settlements is the count of settlements. Period x archeological excavation is a vector of period-relative-to-treatment fixed effects interacted with indicators for each of the three main archeological surveys of settlement we use. These surveys are described and mapped in the data appendix. Period x rainfall is a vector of period-relative-to-treatment fixed effects interacted with average rainfall. Period x temperature is a vector of period-relative-to-treatment fixed effects interacted with average rainfall. River shift (yes/no) is an indicator equal to one if the nearest river was within 5 kilometers in period t-1 the previous period and is further than 5 kilometers away in period t. All regressions include period and grid cell fixed effects. Heteroskedasticity robust standard errors clustered at the grid cell level are in parentheses. Conley (1999) standard errors are in square brackets. * indicates significance at the 10 percent level, ** at the 5 percent level, *** at the 1 percent level.

Table 10: THE EFFECT OF COLLECTIVE ACTION PRESSURE ON SETTLEMENT AND CANAL BUILDING

Dependent variable:	Nr. of settlements	Canal within 5km (yes/no)
	(1)	(2)
	Panel I: Second stage estimates	
Distance to river (km)	-0.0783*	0.0407***
	(-1.75)	(3.76)
Mean dep. var.	1.67	0.71
	Panel II: First stage estimates Dependent variable is distance to river (km)	
River shift (yes/no)	2.990***	2.990***
	(6.97)	(6.97)
Mean dep. var.	14.04	14.04
F-stat excluded instrument	48.5	48.5
R^2	0.87	0.87
	Panel III: Reduced form estimates	
River shift (yes/no)	-0.234*	0.122***
	(-1.84)	(4.49)
Mean dep. var.	1.67	0.71
R^2	0.39	0.62
Observations	6115	6115

Notes: All regressions are estimated using OLS. The cross-sectional unit of observation is a 5x5 kilometer grid cell. The time-series period is an archeological period (see data appendix). Nr. of settlements is the count of settlements. On canal (yes/no) is an indicator variable equal to one if a canal crosses a grid cell. Distance to river (km) is the distance in kilometers to the nearest river River shift (yes/no) is an indicator equal to one if the nearest river was within 5 kilometers in period t-1 the previous period and is further than 5 kilometers away in period t. All regressions include period and grid cell fixed effects. Heteroskedasticity robust standard errors clustered at the grid cell level are in parentheses. * indicates significance at the 10 percent level, ** at the 5 percent level, *** at the 1 percent level.