Future DAMS

Design and Assessment of water-energy-food-environment Mega-Systems

What should we say of Dams who mainly ‘metrics’ mastered? The impact of ‘Dams’

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Abstract

Dams are iconic but controversial manifestations of development. Applied economists have gained unprecedented respect for the 'credibility revolution' toolbox in econometrics. The highly regarded 2007 paper, 'Dams', by Duflo and Pande, using methods from this toolbox reports that dams completed in districts in India in the 20 years from 1970 had some negative effects in their own districts and positive effects in neighbouring downstream districts. We present new data and analysis of the impacts of dams in India using administrative area (district–level) variables, which suggest that dams have no readily discernible negative effects on agricultural productivity in their own districts but positive effects in districts which are actually downstream and have the agro-ecological conditions conducive to irrigation, of which substantial parts have been developed as irrigation command areas. These findings are meaningfully different from those in 'Dams' and underline the need for careful application of the toolbox of the 'credibility revolution' in economics on the basis of a thorough understanding of the sciences involved.

Keywords
Dams, India, Agriculture, Irrigation, Quasi-experiments, Data Validity, Geographic Information Systems

JEL Codes

Q15, Q25, C26, H49, O22

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Acronyms

AVHRR	Advanced Very High Resolution
CBA	Cost Benefit Analysis
Craton	geologic formations of the Indian plate
dataverse	data made available in relation to ’Dams’see Duflo and Pane, 2007
DCW	Digital Chart of the World
DEM	Digital Elevation Model
DP	see Duflo and Pande, 2007
ESRI	Environmental Systems Research Institute
GADM	Global ADMinistrative areas (http://gadm.org)
GIS	Geographic Information Systems
GoI	Government of India
GTOPO30	Global 30 Arc-Second Elevation
IAA	India Administrative Atlas
ICOLD	International Commission On Large Dams
IV	Instrumental Variables estimation
MODIS	Moderate Resolution Imaging Spectroradiometer
MODIS3C1	a MODIS product
NCAER	National Council for Applied Economic Research
NDVI	Normalised Difference Vegetation Index
Shield	southern regions of the Indian Craton
VD	Village Directory (of the Indian Census)
VI	Vegetation Index
VIF	Variable Inflation Factor
WBAg	World Bank Agriculture data base, as augmented by the authors of ‘Dams’.
WCD	World Commission on Dams
WRIS	Water Resources Information System (GoI)

1 Introduction

It is a truth (almost) universally acknowledged that economists in possession of data must be in want of a causal analysis.[1] This truth, which might be termed the 'incredibly credible' revolution, following Manski (2011), in economics, has most recently been acknowledged in the award of the Nobel Prize for economics in 2021 to David Card, Joshua Angrist and Guido Imbens, three economists who have been pioneers in developing and promoting causal analysis in economics (Sveriges Bank, 2021) [2]. Instrumental Variables (IV) analysis has been pre-eminent among these methods, and was used in a novel assessment of the impacts of large dams in India (Duflo & Pande, 2007, 2005; hereinafter 'Dams'). Our re-examination of this paper shows that, unfortunately, not all claims by economists of causal relations based on parts of this toolbox bear examination, even from those with distinguished (James Bates Clark medal and Nobel Prize winning) provenance[3].

There have been many *ex ante* and some *ex post* assessments of the impacts of water resources investments, dams included, and, although economics has played important roles in some such assessments, mainly through the development and use of cost–benefit analysis (CBA) (Pingle, 1978; Banzhaf, 2009; Ansar et al; 2014), there have been relatively few 'rigorous' *ex post* assessments by economists. And CBA, whether performed *ex ante* or *ex –post*, has been associated with much controversy (Whittington & Smith, 2020; Kirchherr et al, 2016; Frank, 2005).

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[1] We refer to the first sentence of "Pride and Prejudice". For those puzzled by the title, we refer to methods characteristic of the recipients of the Nobel Prize for economics of 2021, which have been promulgated in the seminal works on their 'credibility revolution' in applied economics by Angrist and von Pischke (2014, 2009). We also tip the hat to Rudyard Kipling ('The English Flag'), with a touch of Ludwig Wittgenstein's 1922 *Tractatus Logico-Philosophicus*.

[2] Some readers may be surprised by my references to Manski's "incredible certitude". Manski argues that the "certitude of policy analysis [using such analyses] is not credible" (F261). Part of the problem may lie in the contradictory meanings of "incredible" as (originally) not credible, and subsequently as "amazing" (but true); both meanings are widely used to this day. Discussions of certitude in Manski's work generally presupposes credibility based on unchanging "available data and presuming avoidance of deductive errors" (ibid). Credibility is promoted, according to the literature on the "credibility crisis" in psychology in particularly and science more widely, and economics (Duvendack et al., 2017), by reproducibility (same results from same data, estimation model, and estimators) and replicability (similar results from similar data and estimations). "Dams" has never been reproduced; one might consider Strobl and Strobl, 2011, a partial replication (similar data and estimation model, different estimator), although we may note, that paper has not been reproduced either. We add that although data are available, code for the estimators reported in "Dams" are not. Deductive errors will occur of course if the data are wrong, the estimation model, or the estimator, inappropriate or inappropriately computed. Manski describes various categories of "Incredible certitude". There also may be different categories of "incredible credibility", but this is not addressed here. "Dams" does not fit exactly into any of the categories of "incredible certitude" described by Manski. However, we suggest, there may be elements of "conventional credibility" (derived for example from the "halo effect" associated with the authors' status and prestige in the economics profession, the authority of the "credibility revolution" already referred to, and the way the material is written which conforms with professional practices). There may also be an element of "wishful extrapolation" (from the average dam in the past to the impacts of dams in the future, notwithstanding the meaninglessness of the "average dam" when dam sizes and their likely effects vary so dramatically (see below)). Our claim in this work is that the results reported in "Dams" are not credible; some results may have some truth, but this should not be based on the incredible analysis in "Dams".

[3] We do not report a reproduction of 'Dams' here, which will appear in a separate paper. Briefly, we cannot reproduce most of the tables to an acceptable degree of precision, especially those reporting FGLS/FOIV estimations, and those adding variables which are not in the data set provided in the Harvard dataverse for this paper (https://doi.org/10.7910/DVN/MNIBOL). Given the absence of exact description or code for the estimators, we cannot tell whether the unsatisfactory results of our reproduction are due to differences in the estimation commands or to differences in the data we construct from those used in the estimations reported in 'Dams'.

’Dams’ (Duflo & Pande, 2007[4]) was an innovative application of an IV approach, published in a high-profile economics journal[5], during what can be seen as a first wave of “seminal articles” applying IV to new topics and in development economics (see Caciendo, 2021, for applications to issues of history). It has been followed by a number of other studies using the same or similar methods from this toolbox.[6] ‘Dams’ has been cited 748 times (according to Google Scholar, April 2022[7]), including in many articles in the most prestigious economics journals.[8] The paper uses district-level data from India and finds, simplifying, that the average dam causes negative impacts in the district in which it is located, and positive impacts in the neighbouring downstream districts.

The headline and other findings of ‘Dams’ have been influential, especially in lending support to critics of dams. The latter emphasise their negative effects on the populations (and environment) in which they are constructed (WCD, 2000; ICOLD, 1999), as a result of many factors, including poorly compensated displacement of peoples, submersion of land, housing and infrastructure, loss of livelihoods, time and cost over-runs, and so on, and that the benefits such as irrigation “fall well short of targets” (World Commission on Dams (WCD), 2000, p. 43). Results reported in ’Dams’ continue to be quoted approvingly as authoritative, for example very recently by Pradhan and Srinivasan, 2022, when they argue that “weak institutions” may be important causes of adverse distributional consequences of water resources developments (p6). It is therefore important that the causal claims are robust, and that works using the methods from the credibility revolution toolbox are indeed credible.

‘Dams’ claims its results are causal thanks to an identification strategy using geographical features; geographical variables have often been used in the credibility revolution literature to establish identification. In the case of ‘Dams’ it is asserted that a high prevalence of low-to-moderate river slopes is conducive to the location of dams; the shares of different categories of river slopes are the IVs. For identification using these variables to be valid, ie to ensure confounding is addressed, it is necessary that not only do river slopes account for the placement of dams (are relevant), are not themselves affected by the outcomes addressed (are exogenous), and that they do not otherwise affect outcomes of interest (the exclusion criterion). To be specific, in ‘Dams’, districts with a high proportion of low-to-moderate river slopes (1.5 – 3.0 degrees) were reported as having a higher prevalence of dams in 1999 and of numbers of dams completed between 1971 and 1999.[9]

Criticism has been levelled at the use of geographic variables as IVs (see Deaton, 2010, among others). Furthermore, there are flaws in the data deployed in ‘Dams’, in the conceptualisation of the relationship between dams in and upstream of districts, and in the

[4] Unless otherwise stated references to ‘Dams’ are to Duflo and Pande, 2007 rather than the working paper of the same name (Duflo & Pande, 2005).
[5] The *Quarterly Journal of Economics* (QJE) is generally among the top four ranked economics journals.
[6] Strobl and Strobl (2011) is a particularly close application of the same IVs to the impacts of dams in Africa (see also Blanc and Strobl, 2014). Other examples of similar methods include Olmstead and Sigman (2015). Later in this paper we draw attention to problems with some of the data used in ‘Dams’, and note here that its key dataset is also used in Sarsons (2015), Sebastien (2022) and (Guiteras, nd), as well as by many other authors.
[7] 201 citations in Web of Science, which contains references in academic journals.
[8] Whenever we have informally inquired of economists over the four to five years we have been working on this topic, we have always been referred to ‘Dams’.
[9] IV requires instruments that are ‘exogenous’, which entails two assumptions: that they are external to the structural model relating ‘treatments’ to outcomes, and that they only affect the outcome through the endogenous variable, and not otherwise. Deaton (2010) points out that geography instruments may well be ‘external’ but it cannot be assumed that they affect the outcome only through the endogenous variables.

estimations. The most obvious, but not the only, flaw in the data used is in plain sight in the map of average river slopes (‘Dams’, Figure IV; see **Figure 3** below). Since river slopes are also the IVs, this flaw suggests a closer examination of the data and analysis is warranted.

In addition to any econometric problems following from the errors in the instruments, we argue that the more sophisticated estimators reported in ‘Dams’ (Feasible Generalised Least Squares (FGLS) and its IV equivalent Feasible Optimal Instrumental Variables (FOIV)) are not consistent with the datasets described.[10]

We construct a more realistic dataset capturing the relationships between dams and districts reflecting the size of dams, the hydraulic link between dams and districts downstream, and the potential effects of dams within their own district and in districts that are actually downstream; we deploy readily available estimators on data with which the estimators are consistent.

The paper is structured as follows: first, we provide a brief review of the significance of dams in international development. We then provide a plain language summary of ‘Dams’; this makes it clear that using administrative areas (districts in the case of ‘Dams’) as units of evaluation is problematic. Nevertheless, it is of interest to explore whether a plausible approach to the assessment of dams could be made using these units.[11] We describe issues which we have with the conceptualisation (‘the science’), the data, and the econometrics of ‘Dams’. Four key issues we find with the paper need to be addressed in developing a plausible measure of dams and dams upstream (the ‘treatment’ variables) to use in assessing the impacts of dams on districts. These measures must reflect the following: (1) the engineering of dams (the fact that dams sites are determined by geology rather than topography, and that the size of the effective – useful –- capacity of dams is more relevant than the number of dams; (2) the sciences of hydrology (the most important part of which is that water flows downhill) and irrigation (only some soils and topographies have been suitable for irrigation in the Indian context); (3) the outcome measure (of agricultural production) must have observations for each year for each district (a balanced panel); and (4) the econometrics must be convincing (these issues are discussed next and in more detail in **Appendix 2: Dams, river basins, and districts**).

Building on these observations we construct new dams (treatment) variables which reflect the availability of dam capacity to and the potential for irrigation in districts from dams within and upstream of districts, and relate these variables to a new outcome variable reflecting agricultural productivity, together with control and other variables in a balanced panel analysis. We expand briefly on this summary.

First, dams, especially large ones, cannot be built anywhere, as they require geologically suitable sites, and the treatment variables should reflect the size rather than number of

[10]Specifically, the panel data to which FGLS and FOIV are applied is unbalanced, which is not consistent with the derivation of the estimators (see further below). Also, our attempted replications of many of the tables in ‘Dams’ have not been appropriately successful (see the forthcoming Working Paper on Replication of ‘Dams’).

[11] Strobl and Strobl (2011) make a similar criticism. We briefly argue that the alternative proposed by them, Pfaffstetter units, suffer very similar problems to administrative units. Olmstead and Sigman (2015) use five instruments but present only first-stage estimations (establishing relevance) and no discernible justification of the exogeneity assumptions.

dams. Because relatively few dams provide the vast proportion of the effective capacity available to affect districts, the ‘average’ dam is not an appropriate measure.[12]

Second, we need to link dams to the areas of (downstream) districts they may actually have effects on, which will generally be within the same river basin, in the absence of inter-basin transfers through tunnels and/or canals.[13] Since dams will generally only have effects on parts of districts over which the dam has ‘command’ and which are suitable for irrigation, a plausible measure of a dam’s potential effect will reflect the area the dam can have effects on, and similar areas within districts that are (actually) commandable downstream. Irrigation is not feasible or worthwhile everywhere – it depends on agro-ecology, hydro-geology, economics and perhaps politics (Palmer-Jones & Sen, 2003, 2006). Hence, the impacts of upstream dams are likely to occur where there is ample terrain suitable and developed for irrigation.

Third, the agricultural outcome variable used in ‘Dams’ excludes some major states (Himachal Pradesh, Kerala, Assam and Jammu and Kashmir and the other Union Territories), and observations for many of the remaining states are missing for the years after 1987 in a spatially biased way (see **the section ‘3.7 Varying number of cases in ‘Dams’ Table III** below); the specific agricultural production variable deployed in ‘Dams’ has other problems (see **Appendix 5**). The econometric methods of panel analysis are best implemented on balanced panels and it is desirable to have observations on most if not all districts; hence we need an appropriate outcome variable.[14] If the missing observations are biased in any way, concentrated in some regions in some years, for example,[15] estimates, even if legitimate, are likely to have misleading parameters and statistics.

Fourth, following these insights, we set out an empirical approach using districts that requires measures of the effective capacity of dams in and actually upstream of each district in India, with an outcome variable reflecting agricultural productivity, including a few plausible contextual control variables, using transparent panel estimators. Because the sciences of dam capacity suggest that the location of dam capacity is unlikely to be endogenous, we see no reason to use quasi-experimental approaches, but we do report results controlling for contextual variables that likely affect the productivity of irrigation, Our findings do not show that dams have negative effects on agricultural productivity in the districts in which they are located (as reported in ‘Dams’), but that dam capacity upstream is likely to have positive effects in districts where there is good potential for irrigation command areas that have actually been developed.

2 Dams and their evaluation

Water resources investments have been iconic components of modern development since the latter’s inception in the early 17th century, emerging in the 20th century “as one of the

[12] This is how ‘Dams’ interprets its findings (Duflo & Pande, 2007, p 625ff).
[13] Some important cases of inter-basin transfers occur in India. Their accommodation is discussed below. ‘Dams’ constructs its ‘upstream dams’ variable as the sum of all dams completed to date in upstream neighbouring districts. See the section ‘3.4 Neighbours’ below (and **Appendix 2: Dams, river basins, and districts**) for further discussion of this particular formulation of the treatment variables in DP.
[14] In this paper we only explore results using agricultural production, because this is likely to be the prime driver of the other important outcome variable reported in ‘Dams’ – poverty. Poverty measures have limited numbers of observations at variable intervals, and may be considered unreliable at district level.
[15] See the section ‘3.7 Varying number of cases in ‘Dams’ Table III below.

most significant and visible tools for the management of water resources" (WCD, 2000, p xxiv). Towards the end of the last century dams became highly contested (WCD, 2000) but more recently there has been a resurgence in new large dam construction (Zarfl et al, 2015). Water resources developments were important in India's colonial period and dams became the iconic 'modern temples' of India's development since Independence, strongly supported by Nehru in 1954, although in 1958 he was more critical (see Roy, 1999, endnote 4; see also Hart, 1956). India has more than 10% of the world's large dams (Mulligan et al., 2020), most of which have been completed in the post-colonial period, particularly since the late 1960s (http://cwc.gov.in/publication/nrld, last accessed May,2020). India continues to complete and plan new large dams (ibid), and continues to have ambitious plans for dams and other water resources projects (CWC, 2012) notwithstanding reports of plans to shift the focus of water policy towards demand issues and away from dams within the supply-side (Draft New National Water Policy.[16]

Dams have multiple effects, over long periods of time, and cost–benefit assessments have been controversial. While hydro-power (electricity) generation is often seen as the most visible benefit of dams, irrigation, flood control, transport, fisheries, recreation, etc are also objectives of dam construction. Much of the criticism of dams focuses on unintended and often un-anticipated effects, such as displacement and disruption at the dam site and its reservoir, downstream alterations to river flows, and so on. Irrigation, as one of the intended products, by-products, of dams, is supposed to enable agricultural growth, food security, and poverty reduction, although the development of irrigation systems sometimes has negative effects when, for example, replacing existing systems of irrigation leads to poor control of canal water supplies, which can give rise to waterlogging and salinisation. (In the Indian context, see Pradhan and Srinivasan, 2022, and historically see Whitcombe (1974, 1983) but also Stone (1984).

Given the multi-purpose, multi-effect characteristic of water resources developments, conventional economic approaches to the evaluation of dams would typically use some sort of (social) CBA drawing on a multi-sector model to capture the wide-area direct and indirect effects of dams (see, for example, Bell et al, 1982). Bhatia et al (2015) provide an analysis of the Bhakra Nangal dam in northwest India using this type of methodology. Such model-based assessments are generally restricted to particular projects, rather than encompassing all such projects within a nation, and are widely found to be controversial and often unpersuasive (Frank, 2000).

The methods used in 'Dams' were innovative in that they compared areas "with and without dams" (p 602) and, although "regions with relatively more dams are likely to differ along other dimensions such as potential agricultural productivity" (p 602 – the 'endogeneity' problem), the analysis in 'Dams' was "causal" (p 602) thanks to the ability of the econometric panel and IV estimates to control for these other differences. 'Dams' employed a "quasi-randomization" approach to endogeneity based on a "natural experiment", which means that, appropriately estimated, the results can be interpreted as causal. As is well known, the assumptions underlying the IV method cannot be 'tested' and their cogency lies in whether there are plausible arguments that (1) the instrument(s) plays a large role in determining the

[16] https://www.nextias.com/current-affairs/29-10-2021/draft-national-water-policy-nwp

treatment (relevance); and (2) the instrument(s) only affects the outcome through its effects on the treatment and in no other ways (exogeneity). We demonstrate below that neither condition holds for the instruments used in ‘Dams’; also, the instruments were grossly mis-measured.

3 Understanding ‘Dams’

As noted in the Introduction, the headline messages from ‘Dams’, supported by sophisticated econometrics and subject to considerable robustness testing, are that dams have some negative effects on agricultural production and poverty in the districts in which they are located, and positive effects on agricultural production and possibly living standards in neighbouring districts downstream. The IV methods based on geography variables used in the paper have been criticised as unlikely to meet the exogeneity requirement for identification, which can only be supported by attention to the substantive nature of the underlying material model being estimated.[17] In the case of ‘Dams’ this is that river slopes do not affect outcomes of interest other than through their effects on the placement of dams. *A priori* this is most unlikely, since river slopes are likely to reflect other topographic and climatic variables and other variables which may have effects on social and economic phenomena with or without investment in dams. What is notable about ‘Dams’ is that no attempt is made to justify the exogeneity assumption.

Here we discuss the conceptualisation and analysis of ‘Dams’ in more detail.

3.1 The Science

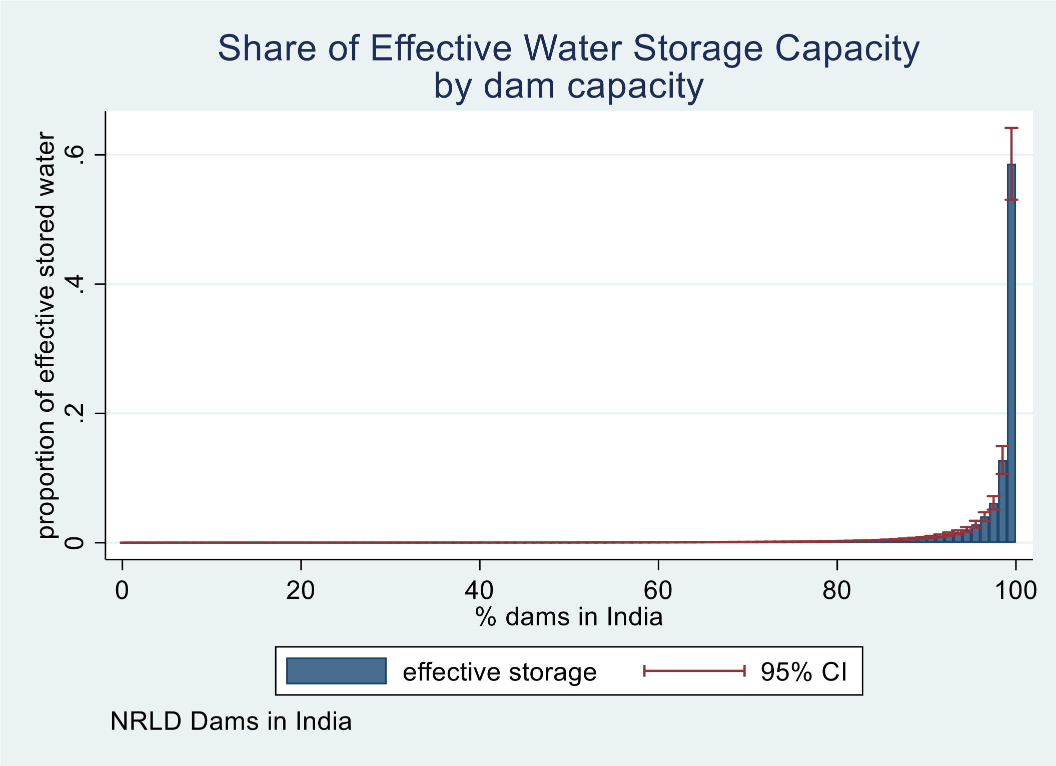
The conceptual framing of the relationships between dams and districts in terms of the number of dams within a district (‘own district dams’) and the number of dams in neighbouring upstream districts (‘upstream dams [in neighbouring districts]’) is profoundly misconceived.

First, dams have huge economies of scale, which means that the ‘average’ dam, or even the median dam, has little meaning when considering either the likely impacts of dams in their own district or in downstream districts, or their costs. Most impacts (and costs) are likely to be associated with the largest (‘mega’) dams; in 2018 around 60% of the effective capacity of dams is stored in 1% (54) of all dams (some 5400) and more than 80% in the 5% largest dams (270 dams) (see **Figure 1**).[18]

[17] Strobl and Strobl (2011) note the identifying assumption (p 440) and conduct a “roughly equivalent J-test of overidentifying restrictions” (p 405) and various robustness tests similar to those in ‘Dams’, including assessing various proxies of prior productivity (p 446). As is well known, “passing an overidentification test does not validate instrumentation”, it is only able to “tell us whether estimates change when we select different sub-sets from a set of possible instruments” (Deaton, 2010, p 431). It is not clear that the robustness tests address the question of endogeneity in a meaningful way.

[18] The figures are even starker for dams completed before 2000

Figure 1: Size distribution of dams

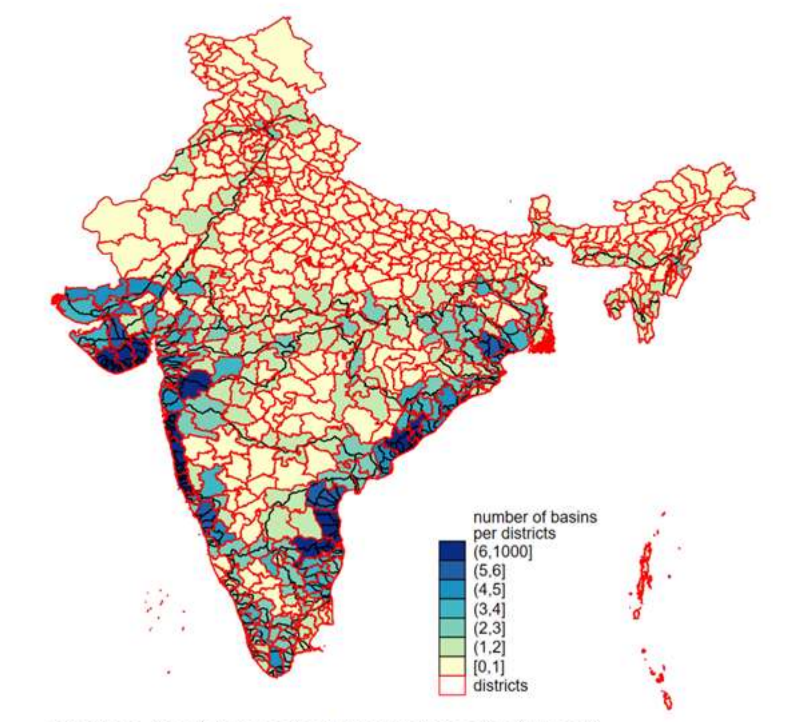


Second, the denomination of the whole of districts as either up- or downstream, or neither upstream nor downstream, conflicts with the reality that river basin boundaries, in which dams will have most of their effects in the absence of inter-basin transfers, do not in India coincide with district boundaries, contrary to the assertion in 'Dams', and as already noted correctly by Strobl and Strobl (2011) in a figure overlaying a map of districts in India on a map of river basins.[19] Thus, many districts are transected by watersheds (the boundaries of river basins) so that dams in them may not flow into the same 'downstream' districts (see **Figure 2**). Further, it is the case that, if we define 'downstream' as having a river from a dam transecting the district,[20] then many districts are both upstream and downstream of a neighbour, and indeed can be upstream and hence also downstream of themselves.

[19] Strobl and Strobl use Pfaffstetter level 6 areas as units of analysis. While these units do fall within the same river basins, many of the problems identified with using districts apply to Pfaffstetter units, as demonstrated in **Appendix 2: Dams, river basins, and districts**.

[20] We call such a district 'hydraulically' downstream. Canals can modify the way in which water from a dam can affect downstream areas, but in the absence of pumping, all areas potentially affected by a dam will be topographically below the outlet of the dam; that is, these areas will be 'commanded' by the dam. This is discussed further below and in **Appendix 2: Dams, river basins, and districts**.

Figure 2: Number of basins per district in India[21]



Third, the 'science' (that water flows downhill) also means that not all of the district in which a dam is located may be affected by that dam, and that the whole area of a district that is at least partly (hydraulically) downstream may not be affected. Furthermore, not all land that is commanded is suitable for irrigation, and some land that can be irrigated is not equally productive; in particular, land which has ready access to groundwater is likely to be more productive whether irrigated partly by canal or not.

Together, these realities mean that it would also be inappropriate to construct variables from the number (rather than effective size) of dams, or for the whole of districts, as done in 'Dams'.[22] Some parts of the dam's own district will not be in the same basin as the dam; dams in the other basins in the same district may flow into other districts, the topographical and geographical characteristics of the different basins in the district may be quite diverse and the characteristics of areas in these other basins are not relevant to areas of the river basin of the dam.[23]

3.2 The data

Analysis of the effects of dams, as with any intervention, using econometric methods on observational data should pay attention to the possibilities of spurious associations resulting

[21] Unless otherwise stated all maps of Indian districts are derived from GADM India administrative areas GIS files. Hydraulic objects are derived from Hydrosheds (https://www.hydrosheds.org/), or from original GIS sources explained in the text.
[22] It could be argued that 'Dams' did not have access to data on the size of dams but the data source used does have the height of dams, which can be a proxy for size.
[23] These points are elaborated in Appendix 2**: Dams, river basins, and districts**. Pfaffstetter units suffer from similar problems in that much of the area of a lower numbered unit are not commandable by a dam in a higher numbered ('upstream') unit, as shown in Figure 3, **Appendix 2: Dams, river basins, and districts**

from a failure to take account of confounding variables. Some geography controls for potential confounding are certainly worth considering, and it is important to include such variables, but they should be accurate, otherwise their inclusion will not perform the role required, and may indeed be misleading. The ability to convincingly execute this type of analysis depends on the unit of analysis, the available and the accuracy of the data.

The authors of 'Dams' use datasets on the number of dams located by their nearest town in a district, by agriculture, poverty, population, incidence of malaria, and other outcome and control variables compiled at district level and which were available at the time. The dams variables are from the International Commission on Large Dams (ICOLD); agriculture data are from the World Bank;[24] population data from the Census of India (University of Maryland India District Project). Other data are attributed to colleagues, and topography (district elevations, district slopes and river slopes) and geography (district area and river length) variables were constructed by Geographic Information Systems (GIS) methods by research contractees.[25]

There are two crucial and several lesser problems with the data deployed in 'Dams', in addition to the science problems discussed above. The first data problem is that the river variables are incorrect. The second concerns the identification of districts' neighbours and their type (up/down/neither).[26]

3.3 River slopes

As noted in the introduction, the possibility that the river slope variables were wrong is in plain sight,[27] and is obviously at odds with common knowledge of the topography of India (see **Figure 3**). For example, there is no reason to believe – considering the elevations depicted in the RHS panel of **Figure 3**, which reflect common knowledge of the topography of the south Asian subcontinent – that average river slopes in neighbouring districts in the Himalaya of Uttarakhand, or that neighbouring districts in Arunachal Pradesh differ in the way shown in the LHS panel of **Figure 3**. These districts, however, do not appear in the 'Dams' agriculture dataset and might not affect the areported there. More concerning for the

[24] Some of the agricultural variables, those representing agricultural production, in the World Bank dataset were extended from 1987, the last year of the original dataset, to 1999, by the authors. The base World Bank Agriculture (WBAg) dataset also had been and was being used by colleagues. These extensions have many missing observations, so the dataset is not 'balanced' (representative) in an appropriate way, a point we return to below when discussing the econometric methods. Data from only 6 major crops seem to be included in the more recent years.

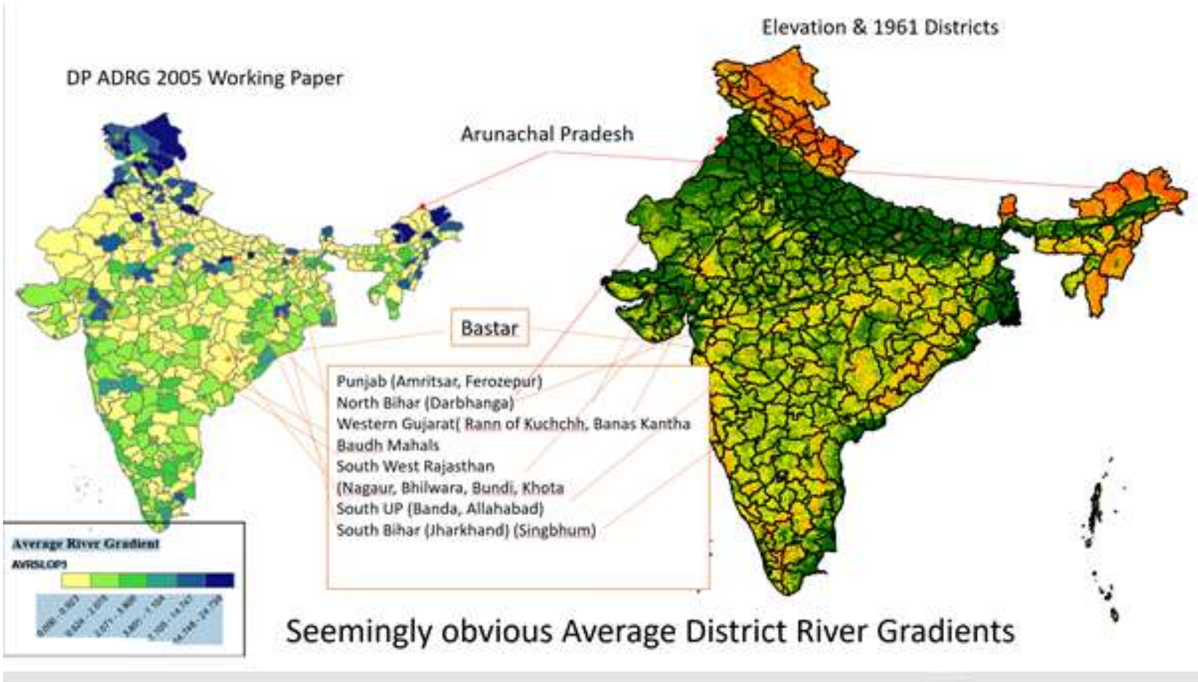
[25] The GIS methods use a Digital Elevation Model (DEM) file in which each pixel represents an area of the Earth, and has a location and elevation to estimate topography and geography variables after imposing a map of the districts of India which is used to select those pixels that are within each district. The DEM can be used to calculate slopes, and the river network file can extract those pixels which correspond to rivers. The extracted district elevation or slope variables are then divided into ranges and entered into estimations as the proportion of pixels in the district. One category (the lowest) is dropped from regressions. The GIS variables were constructed at CEISIN, but the accuracy and relevance of these variables are presumably the responsibility of the authors of 'Dams', rather than research assistants or contractees, who are acknowledged "without implicating".

[26] Since we argue that the neighbour-type categorisation for all of a district is not hydraulically justified, and district neighbours can be both upstream and downstream (both) there are no 'correct' neighbour types. Our approach is to denominate dams as upstream, irrespective of whether they are in a neighbour, rather than utilise variables defined as "[all] dams in neighbouring districts"; see further below.

[27] See Figure 4 in Duflo and Pande (2005), and Figure IV in Duflo and Pande (2007); the former is reproduced here in the left hand map of Figure 3, and our reconstruction of this map is the LHS in Figure 4, using the river slope category variables in the dataverse files, since these files do not contain district "average" river slopes. As can be seen our reconstruction is very similar to the maps in both the 'Dams' papers. Some commentors on our work found it very difficult to accept the obvious presence and obvious nature these errors.

analysis in the paper is the lack of consistency in the river slopes in districts either side of the Narmada River, which are included in the 'Dams' datasets and analysis, and where there are many dams in and upstream of (neighbouring) districts. Among the districts of this region are some with many dams themselves and that have many dams upstream, which means that the river slopes variables in these districts are mismatched to their numbers of dams.

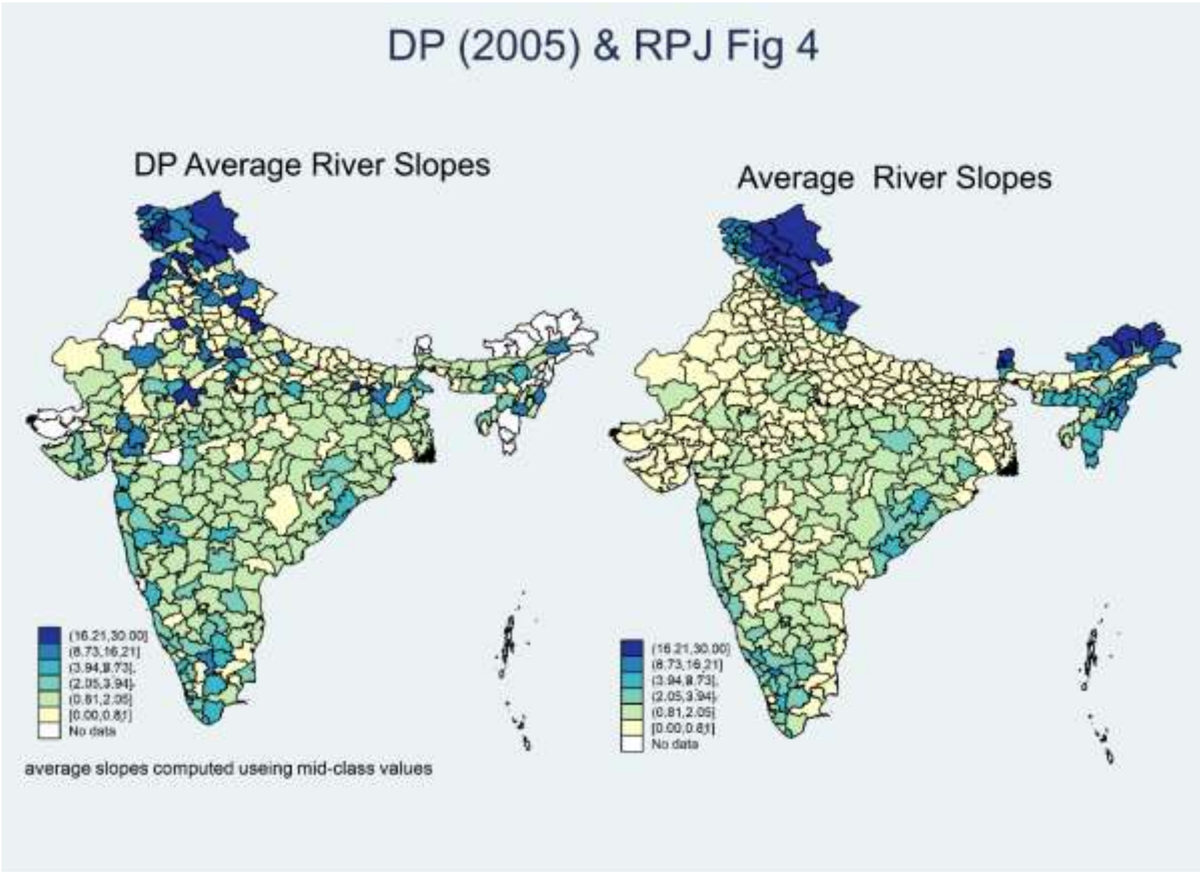
Figure 3: Average river slopes



Sources: left hand panel Duflo and Pande, 2005, Figure 4, which is substantively identical to Figure IV in DP, 2007; right hand panel authors' GIS from GTOPO30 and GADM.

In the right hand panel of **Figure 3** we see far more convincing spatial patterns of average river slopes (the left hand panel reproduces the figure (**Figure 4**) in Duflo and Pande (2005) using variables from the dataverse). The river variables we construct confirm that the river variables, river slope categories and length, are all incorrect in the same manner as are average river slopes (ie in the districts where average river slopes are in error), seemingly because of mis-merging of datasets (because the descriptive statistics over all districts we produce are similar to those in 'Dams' Table II – see our forthcoming Working Paper 'Replication of "Dams"').

Figure 4: 'Dams' district average river slopes



Sources: author imputed average river slope from dataverse file (Left Hand Panel) and GTOPO30 DEM[28] (right hand panel) and GADM 1991 districts.

This problem of erroneous river slopes is crucial because it raises the possibility that the empirical support for the IV strategy is not reproduced when the correct data are used (see the section '**3.5 Econometrics**' below).

3.4 Neighbours

The second problem – the identification and categorisation of neighbouring districts and their type – is not obvious in 'Dams', and cannot be diagnosed using the dataverse files, which contain no variables indicating which districts are neighbours, nor, obviously, what their 'neighbour type' is (upstream, downstream or neither).[29] In part because we needed to compute correct river variables for both own and for 'upstream neighbouring' districts (and

[28] Last downloaded from WebGIS, 2022.

[29] Another problem with the data is that it is not clear how the district topography and geography variables were computed, especially for districts whose boundaries changed between 1961 (the approximate date for the boundaries of districts in the agriculture data set) and 1981, the period of the poverty dataset. It appears that the boundaries of districts of observations with the same name were those for 1991; thus the values for Srikakulam for 1981 are computed for the boundaries in 1991 after Vizianagaram had been formed from parts of Srikakulam and Visakhapatnam in 1979. Thus, the value of the proportion of the area in the lowest elevation category for Srikakulam in both the poverty and agriculture datasets is 0.9192, while that for Vizianagaram after its formation mainly from Srikakulam is 0.7691;. the value for Srikakulam before the formation of Vizianagaram should be 0.8001, reflecting the separation of an area of lower elevations to form Vizianagaram. Similarly, Vishakhapatnam has the same value in 1981 and the agriculture data set notwithstanding the transfer of some territory to the newly formed district of Vizianagaram in 1979.

other neighbour types), we reverse engineered the neighbour categorisation,[30] and computed new district dams, and geography and topography variables.[31] Only our river variables differ meaningfully from the variables in the dataverse when using the 'Dams' neighbour type categorisations.

Further, when we compute actual neighbours using standard GIS methods,[32] we find a number of errors in the denomination of neighbours, and some obvious mis-categorisations of neighbour type; for example, Nashik is upstream not downstream of Jalgaon (see the 'Neighbours' and 'Direction' sections in Appendix 1). There is no reasonable way to denominate the type of a neighbouring district for all neighbouring districts, so there can be no 'correct' assignment of a "type" to a (actual) neighbour districts. We use a different way to identify dams that are upstream, and the areas within districts that they can affect, as explained below[33].

3.5 Econometrics

The key analysis in 'Dams' is of the base and extended World Bank Agricultural dataset (WBAg) to which standard Ordinary Least Squares (OLS) and Two Stage Least Squares (2SLS),[34] and novel FGLS and FOIV estimators are applied. The key results using the World Bank Agriculture data and the most sophisticated estimators are presented in 'Dams' Table III (see **Appendix 1: Additional tables**) and it is the data and estimators used in this table that we concentrate on here.[35] The agriculture results are key because it is likely that the findings in regard to poverty would arise through effects on agricultural productivity and related incomes and employments, and price effects (Dutt & Ravallion, 1998; Palmer-Jones & Sen, 2003, 2006).

The first econometric problem concerns the likely collinearity among topography and geography variables, which makes interpretation of regression coefficients problematic. The second econometric problem concerns the varying number of case numbers reported for FGLS and FOIV estimations in 'Dams' Table III Part B, row *N* (reproduced as **Appendix 1 Table 1**

3.6 Multicollinearity (and wrong river variables)

Multicollinearity leads to instability and unreliability in coefficient sizes and in statistical significance results. Topography variables such as those used in 'Dams', which are either

[30] We could do this because the district areas (river lengths) of some combination of districts in the dataverse data should sum to the equivalent neighbour-type value. For example, for district A some combinations of the areas of neitghbouring districts must sum to the value of the 'upstream districts area' of district A. Late in our research we were provided with some additional data files which confirmed that our reconstruction of the neighbour allocations was identical to that employed to construct the dataverse variables.

[31] See our forthcoming Working Paper 'Replication of "Dams"'. We use a more recent and detailed dataset on dams (Central Water Commission, 2019), and our own topography and geography variables constructed from the same or similar raw data.

[32] As noted, we believe that 'Dams' uses the 1991 set of districts and merges them for sets of districts in the datasets that correspond to earlier periods or categorisations.

[33] It would have been possible at the time and with the data available then (the early 2000s) to follow all of our approach, although a different (but plausible) approach to denominating the irrigable areas in a district would probably have been required. We have not executed such an approach, but further details may be obtained on application to the corresponding author.

[34] 2SLS is applied in other tables to the WBAg data, but not in Table III.

[35] A more extended discussion of 'Dams' is made in our forthcoming Working Paper on the 'Replication of "Dams"'.

the IVs or ‘controls’ for geographic characteristics, are likely to be collinear. ‘Dams’ includes three sets of topography variables, namely the proportions of pixel centroids[36] in districts that fall into each of four categories of district elevation, and district and river slopes, with the lowest category excluded to avoid complete collinearity. Given the way the district and river slopes are computed it, is highly likely that they will be associated particularly given the relatively large pixel size.[37] Districts with a high proportion of low slopes are likely to have a high proportion of low river slopes, and in India they are also likely to have low altitudes (this may not be the case in a high altitude plateau or for a geological formation such as Death Valley in California). In the Indian subcontinent, where most of the lower altitude areas (<250 meters in the categorisations employed in ‘Dams’) are in the Indo-Gangetic plains and the great deltas, the proportions of the district and river slopes that fall into the lowest categories are likely over 0.80–0.90 or more, so that the proportions in each of the higher district and river slope (and elevation) categories are likely to be near zero (and correlated).

Practically the whole of the Indo-Gangetic plains have elevations below 250 meters yet can be more than 1,000 kilometres from the outlet to the Bay of Bengal – hence practically all slopes in most of these districts are in the lowest slope category. Consequently, most of the rivers in these plains also have negligible slopes, resulting in widespread waterlogging and frequent flooding, especially in the lower reaches. Many districts in these plains are entirely at low altitude and of necessity have more than 90% of their areas with low district and river slopes. The concomitant of the association of low district and river slopes with low elevations is that it is likely that high proportions of higher altitudes will be associated with higher proportions of district and river slopes. Indeed, this is the case, with the associations of lower district and river slopes having correlation coefficients of greater than 0.95 (Panel A in

Appendix **1** ***Table***).[38] The association with low elevation is less extreme, at r> 0.2, which is still statistically extremely significant; this is understandable, given the vast river flood plains of some the major rivers of peninsular India which have elevations greater than 250m. (Panel B in **Table 2**, Appendix 1: Additional tables), reports the correlation coefficients among topography and geography variables in the dataverse agriculture data; the correlations with river variables with the other geography and topography variables are of course much, but wrongly, lower.)

3.7 Varying number of cases in ‘Dams’ Table III

There are also subtle indications that some of the econometric estimations used by the authors of ‘Dams’ are not consistent with their assumptions. The most concerning issue is

[36] The geography variables are computed from a Digital Elevation Model (DEM) which is a raster file where each cell (pixel) covers, in this case, 8km^2. The Pixel centroid is at the geographic center of the pixel and is taken to represent the whole of the area covered by the pixel.

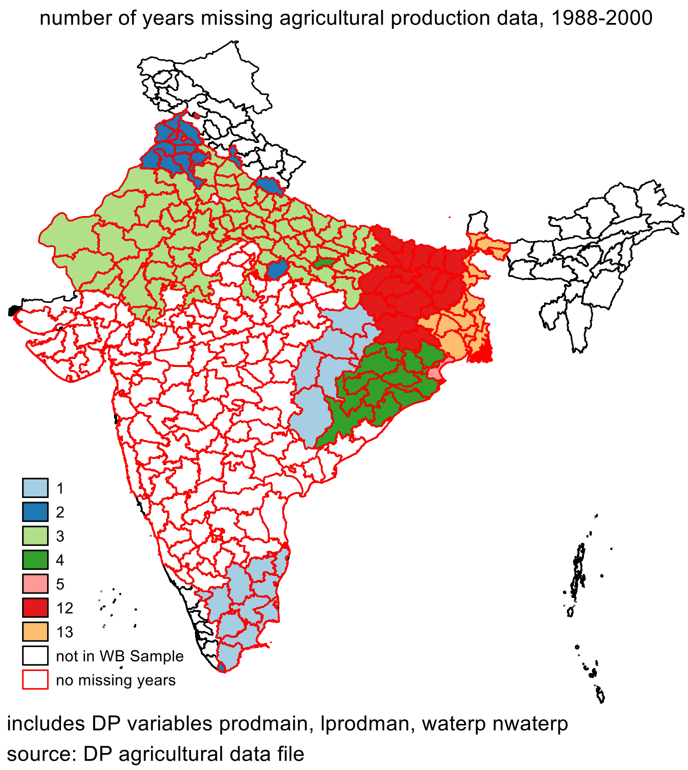
[37] Slopes are computed between the elevation of the pixel in the DEM at its centre and those of each of its neighbours. Obviously the slopes that are calculated will vary with the size of pixel (in 2005 Duflo and Pande refer to pixels as “polygons” (p14), and in 2007 as “cells” (p641). The size of pixel will also affect the river slopes, which are just the slopes of the pixels under the river trace; larger pixels will include areas further away from the actual river course and hence reflect more of the district than the area actually under the trace.

[38] This is particularly likely because of the way these variables are computed using heights for pixels that are 8km^2. We use the same DEM data source as ‘Dams’, so, although district boundaries may differ somewhat, our computed slopes are directly comparable with those in ‘Dams’. E060N40 downloaded from WebGIS, 2022, http://www.webgis.com/terr_world_03.html.

evident in the case numbers reported in the paper.[39] Our understanding of the estimators deployed is that they require "balanced panel" data (Hansen, 2007 and personal communication, 2021). That is, for every district there should be an observation in every year. Varying case numbers (which are not multiples of numbers of districts and numbers of years), indicate that the data used were not a "balanced panel". Readily available code to estimate regressions using FGLS fails when applied to an unbalanced dataset (e.g. the Matlab 'fgls' routine). A seemingly closely similar routine in Stata also assumes a balanced panel and will fail unless the 'force' option is used.[40]

The districts and years which are missing in the agricultural production observation of 'Dams' Table III are spatially concentrated in certain states (see Figure 5) and in the years after 1987.[41] Figure 4 shows the spatially concentrated distribution of missing observations of the agricultural production and its log[42].

Figure 5: Districts with missing agricultural production observations in the extended WBAg data



Recall that 'Dams' Table III deploys FGLS and FOIV estimators. Both make use of the re-weighting of variables to take account of serial autocorrelation using a method and code

[39] See 'Dams' Table III reproduced as Table 1 of Appendix 1: Additional tables.
[40] According to Stata Technical Support, the 'forced' option assumes that all missing observations within panel variables (for some years for some districts) are sequential; that is, if there are missing years within the estimation time span, observations from the later years are assumed to follow the year of the last non-missing observation, and so on. Hence, these non-sequential observations will be moved to a different year. This process does nothing to address any spatial pattern to the missing data. The pattern of missing data is discussed below.
[41] See Figure 1, Appendix 1: Additional tables for missing years. It is not possible to accurately map the areas present or missing from the analysis because of the imprecise way in which observations of variables for districts in the WBAg dataset were constructed, as explained in footnote 29.
[42] In the dataverse files the log variable has missing values where the non-log variable has zeros, for which, of course, the log is not defined

from Christian Hansen (personal communication and Hansen, 2007). The FGLS results are reported in Panel A of Table III, and the same adjustment is then, apparently, made in the first stage of the FOIV estimations (reported in Panel B). There are no 'off the shelf' computer routines to conduct these estimations that work with the 'Dams' data, and we have not been able to replicate them to an acceptable level of precision (1 ore more decimal points).[43] The key point is that the data should consist of a balanced panel for the estimators reported as used in 'Dams', which is evidently not the case.[44].

3.8 Topography variables and the exclusion restriction

A key requirement of an IV is that it meet the exclusion restriction, that they affect outcomes only through their effects on the endogenous variable(s). Topography and geology variables in India are, however, probably associated with public investments such as roads, which are likely to be associated with agricultural productivity, poverty, and so on. We constructed indexes of the presence of village infrastructure variables in the 2001 Indian Census Village Directory (VD) files available from Meiyappen et al (2018). Three principal components with eigenvalues greater than 2 account for more than 68% of total variation. One of these principal components, associated with poor infrastructure (lack of *pacca* and prevalence of mud or foot approach roads or paths, and lack of electric infrastructures) is associated with prevalence of steeper river slopes.[45] These relationships are likely to be complicated by the simultaneous nature of dam and public investments; the construction of large dams requires improved infrastructure facilities and is often associated with compensatory public investments for those displaced or disadvantaged by the construction, however imperfectly. But, as shown below (see section , dams are often placed in districts with 'rugged' topographies, relatively remote from major cities, with unfavourable underlying geologies and associated soils (ie low prevalence of alluvial geologies).

For the rest of this paper we do not use FGLS or FOIV, as it does not seem likely that the test statistics over-reject the null of 'no effect' of dams in own district or upstream, in which case autocorrelation may not be a great problem for our inferences, and is anyway less a priority than framing the science of dams better and getting the data right.

4 So what can we say about the effects of large dams in India? [46]

As noted above, notwithstanding the incongruity of administrative and hydraulic units (districts and river basins), we can see merit in attempting to construct treatment and control variables which credibly reflect the nature of dams and their effects. Addressing the issues identified in 'Dams' requires solutions that take science, data and econometrics into account holistically.

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[43] We would have been interested to observe the results using the 'correct' river variables, even with the dubious neighbour-type constructions.

[44] It is likely that Hansen's correction for autocorrelation could be carried through when observations are missing at random (Hansen, personal communication; see also Sarzosa and Guiteras, 2012). The extended agricultural production variables in the 'Dams' dataverse are not missing at random, in either time or space – see **Error! Reference source not found.** and **Error! Reference source not found.**.

[45] Details are available from the corresponding author. The relations between the location of dams, dam capacity and village public goods will be discussed further in our forthcoming Working Paper.

[46] This section cuts to the present chase; there was a long and circuitous route here which will be reported elsewhere.

4.1 Better science, data and econometrics

First, we need data on the size and location of dams, which allows us to link them to districts in a more 'scientific' way.[47] Second, we need a new metric which better reflects the potential effects a dam could have in its own and in downstream districts, in particular its potential effects on irrigation and agricultural productivity. Terrain suitable for irrigation will generally have relatively flat, fertile soils, with good drainage, and in the context of canal irrigation in India, suitably abundant groundwater which can be used by farmers to supplement unpredictable, unreliable and uncontrollable canal water supplies (see, for example, the discussion of canal irrigation in India in Chambers, 1989; and more recently Pradhan and Srinivasan, 2022). In many areas irrigation developments are required to make use of the water resource created by dams. This is especially the case where originally groundwater levels were originally low. Thus, in large areas of the Indo-Gangetic plains far from natural water courses prior to the advent of canal irrigation groundwater tables were very low; with the advent of canal irrigation, over time water leaked or spilled from canals, raising groundwater levels in many areas of India and making groundwater based irrigation more feasible and economic (Whitcombe, 1972; Michel, 1967).

Third, we require a credible district-level outcome variable that is a 'balanced' panel for all districts over an appropriate time period.

Fourth, we require valid ways of addressing the potential endogeneity of dam (capacity) placement, should this be of concern. Since the topography variables used in 'Dams' are neither credible (they do not directly determine suitable locations for dams) nor econometrically appropriate (they are highly collinear with other topography variables) correlates of the placement of dams (or dam capacity), we propose the use of geology as the more appropriate variable associated with the location of dams, as explained below (see the section '**4.4 Addressing the endogeneity of dams – geology and dam placement**').

Before describing our variables, we need to explain how we deal with one problem in constructing district-level variables in India for different datasets, namely specifying district borders. There is also an issue over which source to use for the location of rivers for river variables.[48]

Which districts and rivers?

It is not clear which district boundaries were used in 'Dams', but we suspect that a GIS map corresponding to the 1991 Indian Census set of districts was used to construct the geography and topography variables (see **Appendix 4: construction of topography and geography variables, 4.1 Districts** which describes briefly our construction of geography and topography variables). How these variables were computed for the sets of districts in the

[47] Our data on dams (Central Water Commission, 2019) has information on the location of dams (generally quite accurate latitude and longitude), and several variables which can be considered proxies for dam capacity. As noted above, the 'Dams' source only has the nearest town and river basin, and the height of the dam. With some additional GIS effort 'Dams' would have been able to use the same approach that we developed, by 'moving' the dams to the nearest point on a candidate river near the nearest town.

[48] The sources specified in 'Dams' do not resolve either of these problems.

‘Dams’ datasets which correspond to earlier dates and different total numbers and boundaries is not described.[49]

Asher and Novosad (2019) discuss the issue of which ‘districts’ to use in constructing datasets at district level for India and use ‘super-districts’ whose boundaries largely do not change over the time periods of the district datasets they deploy. We do not use their solution (‘SHRUG’ districts) because it involves amalgamating districts into larger spatial areas which are more diverse than is appropriate (and gives fewer observations). Our approach is to allocate *taluks*, the third level of Indian administrative unit, to districts for each dataset, using overlays of the maps of the Indian Administrative Atlas as a guide to which district a *taluk* belonged to at that time. In only a few cases does it seem that a *taluk* has been split. We undertook some tests using the ‘consistent’ SHRUG district boundaries, but our approach does not seem to make much substantive difference.

As shown in appendix **4.1 Districts**, it appears that ‘Dams’ simply used the value in 1991 of the district with the same name (in 1991) as the value for the earlier period. This is clearly inappropriate.

There are also problems with the source of data for rivers reported as used in ‘Dams’ (see **appendix 4.2 River traces**). This will affect the river length and river slope categories (and average river slope) variables. The size of river to be included will make a very large difference to the length and also the slopes of rivers; if small rivers are included, then the total length of rivers will be higher, and because steep slopes are associated with smaller catchments (on the whole) inclusion of smaller rivers will make for a higher proportion of steep river slopes.

In addition to having an unspecified (and arbitrary) minimum river size, the Digital Chart of the World (DCW) rivers GIS files have traces for both sides of braided rivers and lack ‘centerlines’.[50] Also, inspection suggests the traces are inaccurate in many districts, for example those along the northern Indian border in the Himalaya. Our river variables are constructed from the Hydrosheds river network files.[51] It turns out that the results using different sources of river networks do not make much difference, in part because we do not use river slope variables, but that could not be known in advance.

[49] ‘Dams’ reports that the 1961 Indian Census districts are used in their agriculture dataset. In fact, the WBAg dataset (Dinar et al, 1998)) does not specify the boundaries of the districts and does not correspond exactly to either the 1961 or 1971 Indian Census sets of districts (Surat in the 1961 Census is split into Surat and Valsad in WBAg data). The districts in the poverty and other datasets correspond to the 1981 India Census set of districts. The number and boundaries of districts changed between the various (original) datasets used. It is not clear from the dataverse files how this problem was resolved. We use districts constructed for each dataset by combining the *taluk* most likely to have been included in the relevant district in each dataset; we determine which *taluks* were included by overlaying the GADM level 3 shape file on digitised and geolocated versions of the maps in the India Administrative Atlas.

[50] There are various sources of DCW rivers available at the time of data construction and we computed river variables from them and our preferred source. Because of the relatively large size of the DEM pixels, the choice of river vector source does not make a great deal of difference (quite similar sets of slope pixels to compute river slope variables are extracted by all the river vector files; district river lengths from the different sources differ somewhat more, but again this makes little difference in part because of high collinearity with district area).

[43] these are available (May, 2022) at: https://www.naturalearthdata.com/downloads/10m-physical-vectors/10m-rivers-lake-centerlines/

4.2 Effective size of dams

To address one of the issues in ‘Dams’, we need data on dam size; we use ‘effective size’ – active capacity. These data are available in the Central Water Commission 2019) document,[52] which also contains the location (longitude and latitude) and some other characteristics of more than 5,500 dams in India.[53]

The active volume of water stored in a dam is the maximum volume that can be released, but this volume is only relevant to downstream areas in the absence of prior diversion and/or conveyance losses. Dam releases will generally be made either for hydro-electric, irrigation, flood control or navigation purposes (other uses commonly include fisheries and recreation). Even in the case of releases for irrigation, which may not be well or primarily coordinated with irrigation demand, losses will occur as a result of evaporation, seepage and legal or illegal diversion to irrigation (or other uses) sequentially with upstream appropriations ordinarily having prior access (giving rise, for example, to the well known ‘upstream-downstream’ problems of, usually, better access, but sometimes to problems such as waterlogging).[54] Many of these diversions,[55] or losses, will be associated with distance, with losses likely to be highest closer to the dam (where flows have larger volume and greater surface and conveyance structure areas).

We compute river (drainage) course for each (significant) basin from the Digital Elevation Model (DEM),[56] and ‘move’ dams to their nearest river and then compute the length of drainage courses on which they are located to the ocean (or border of India) using standard GIS modules.[57] This drainage path from each dam touches the boundary or enters districts that are (hydraulically) downstream. This path identifies which dams are hydraulically upstream of a district and allows a measure of the hydraulic distance (length of river trace) from the dam to the district (or irrigation command area within the district). There are problems constructing these drainage courses, particularly where the slopes are very low. In these cases, are mainly in the watersheds of the Indus and Ganges basins, or in coastal areas with low slopes, small rivers, and few dams. In the former there are no dams, while in

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[52] NRLD (2019), http://cwc.gov.in/publication/nrld (last accessed May 2022) is a .pdf file. Many corrections are required to the data we captured from this file, involving locating dams where there are evident inconsistencies in the location, such as lying outside the boundary of India. Errors undoubtedly remain, the most worrying of which is that quite a number (about 1%) seem to be located at the same location as another dam; such dams are discarded in the present work.

[53] We cross-referenced the NRLD dams to data scraped from the GoI Water Resources Information System (currently https://www.indiawris.gov.in/wris/#/) (WRIS)There have been various iterations of this site, and some of the data we downloaded seems currently unavailable. The WRIS data has some advantages but lacked measures of the effective capacity of dams. The two sources largely had the same dams in very similar locations. Both sets can be linked to recent ICOLD dams data, but this also does not contain several useful variables.

[54] These issues are recently discussed in Pradhan and Srinivasan, 2022.

[55] Ideally one would take account of the actual diversions from releases, by, for example, taking account of the actual irrigation schemes or other diversions of water from each dam. With the data presently available this is not possible.

[56] Further details of our GIS methods are available from the corresponding author at our discretion. We use some 120 basins, which enables more than 5,000 dams to be located on a river. The remaining dams are mainly in coastal areas where we were effectively unable to compute river courses. These dams are added to the districts in which they occur and are never upstream of other districts, together with their shortest route to the coast.

[57] A number of problems were encountered in the GIS data construction by the corresponding author; most of the GIS data construction is in code using Stata (version 16 or later) and ESRI ArcGis Pro python 3 (arcpy). We found some dams were located in the exact same position as other dams; the more recent dam was discarded (about 1% of all dams), but this should be subject to further examination.

the latter we use geodesic distance to the nearest ocean (or border of India) to measure distances.

4.3 Potential for irrigation in districts

As for the second solution (to take account of the potential for irrigation from the dam in each district), while there are statistics on irrigation at district level, they are for whole districts and do not respect the fact that not all of a district may be affected by a dam. Only those parts of a district that are hydraulically 'commanded' by the drainage course from the dam can benefit from a dam.

Our first attempt to construct a variable representing the potential for irrigation in a district was simply the length of river course from the dam within the district. We computed the lengths of drainage course from the point where it first encountered the boundary of each district to its exit; lengths which were within 1km of a boundary were allocated half their length. This was the only measure we could think of before obtaining a GIS file of the areas of irrigation schemes within India.[58] This gives us the following equation:

Equation 1 effective size weighted by distance to and length of drainage within the district

$$\sum_{dams_i^d} \langle es_i * (1-b)^{dist_{i,d}} * \left(lengthWithin_i^d + 0.5 * \ lengthAlongBorder_i^d\right)\rangle$$

Where *d* is district, *i* is dam, es_i^d is effective size of dam *i* affecting district *d*; *b* is the negative exponent; $lengthWithin^d_i$ and $lengthAlongBorder^d_i$ are the distances within and along the border of district *d* of the drainage course from the dam *i* in district *d* hydraulically connected to dam_i; *dist* is the hydraulic distance between the dam and command area *j.* Thus, this metric takes account of the size of dams, their distance from areas irrigable from this dam, and the length of drainage path within the district, taking account of those lengths shared with a neighbouring district.

Using this measure of the effects of dams within districts (summing the negative distance weighted effective capacity multiplied by this measure of the potential effect of a dam in the district over all dams actually upstream), and anticipating the results reported below (**Table *5***), we found no statistically meaningful coefficient on this treatment variable.

4.3.1 Irrigation potential within districts – actual command areas

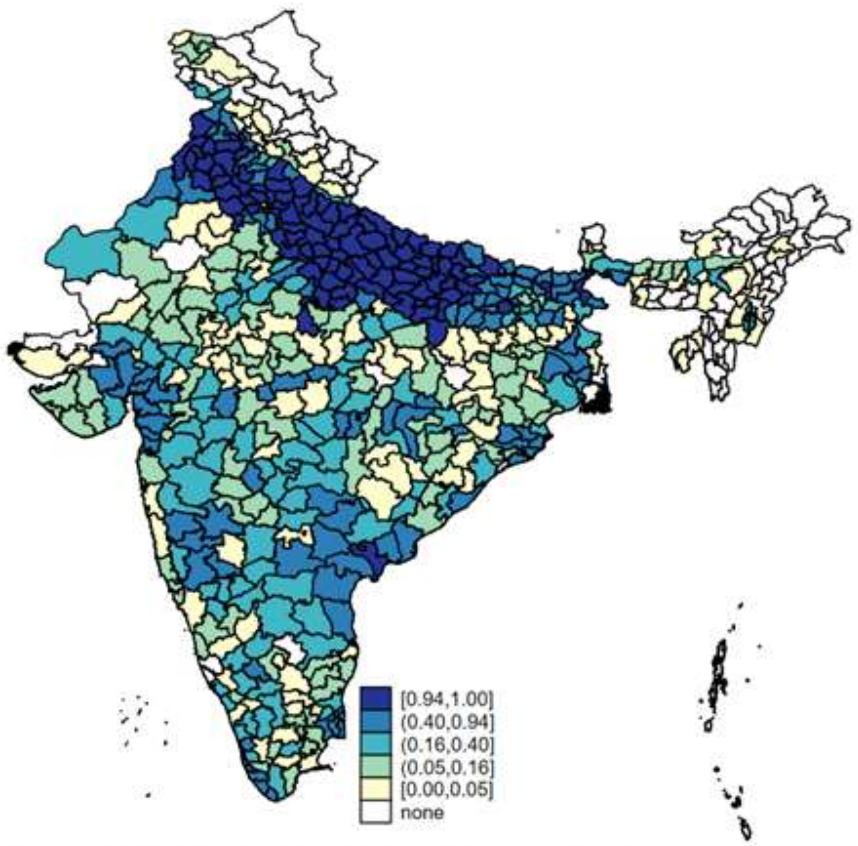
Late in our research we obtained a file of 'irrigation command areas' showing the spatial extent of command areas in India.[59] This appears to be a fairly comprehensive set of irrigation projects constructed or in progress up to the late 2010s. There are no useable variables in this file (for example data on start, or completion) other than their location, which is presumably fairly approximate.

[58] We have another source which reports the districts affected by major and medium irrigation projects in India; this does not show the areas within districts in these projects so it has limitations for constructing variables representing the potential within an affected district for irrigation from a dam. We conducted analyses using dummy variables for the presence of irrigation projects within districts which showed positive and statistically significant coefficients with our outcome measures. Details can be obtained on application to the corresponding author.

[59] Obtained on request from WRIS in 2021.

Figure 6 shows the proportion of districts' areas under the command areas in this file.[60] The figure shows the distribution of (all) command areas in India. As is well known, most of the districts in the Indo-Gangetic plains and the major river deltas (Mahanadi, Godavari, Krishna, Cauveri) are under command areas, but so are significant areas in the upper and mid Krishna and Godavari basins, in the mid to upper Narmada, lower Tapi, upper Cauvery, lower Mahanadi and Damodar basins, and so on. While not commonly referred to as deltas, districts at the bottom of the Tapi, Narmada, Mahi and Sabarmati, have high proportions under command areas. There are command areas in the Bikaner and Jaisalmer, which are in the plains of the Thar Desert between the Indus, Ganges and Sabarmati basins. These areas (classified as areas of inland drainage) are traversed by ephemeral rivers with low flows, and have very few upstream dams. As noted elsewhere, irrigation command areas in these districts are supposed to obtain water from the Indira Gandhi (Rajasthan) canal fed by inter-basin transfer canals which conveywater from more westerly rivers of the Indus basin to the lower Beas, from which they are diverted towards the Thar Dessert (Rangachari, et al., 2006).

Figure 6: Proportions of districts under irrigation command areas



Sources: WRIS command area shape file. 2001 districts

[60] Considerable 'cleaning' of the file was required. See below.

4.3.2 Weighted effective dam capacity: dam size, distance to, and area under command areas within districts

In this section we describe treatment variables for dams in districts and dams upstream which take account of the area potentially irrigable from each dam within districts; these variables incorporate the size of dam, its distance to the district and the irrigation command areas within districts. The first two components of our variables have already been described. Next we describe the metric for the irrigation areas within districts.

Using the file of locations of irrigation command areas within districts, we construct three variables representing the potentially irrigable area within a district from dams hydraulically upstream. The first variable is the area under any command area within the district that is transected by the drainage path from a dam within the district or one that is hydraulically upstream; this is discussed further below. The second variable we construct is the area of irrigation command areas which are not transected by any dam; this variable is included as 'other command areas'. The third variable is that part of the district which is not under any command area; it is assumed that this area is not affected by dams even when transected by drainage courses from dams, and it is not included in regressions.

We merge these "potential irrigation" measures with the dam capacity and distance measures to construct three treatment variables. The first treatment measure we construct takes no account of the irrigation command areas within districts, taking account only of the effective capacity of the dam and the distance from the dam to the first point at which it touches the boundary of the district.

The second treatment variable reflects the potential for irrigation in a district through the length of the drainage course within (or along the border of) the district, together with the distance from the dam to the first point at which it touches the boundary of the district and the effective size of the dam. This measure for each dam is summed over all dams hydraulically upstream of the district.

The third treatment variable aims to capture the potential effect of dams in districts using the command areas within districts with which the drainage from the dam intersects to measure the potential for irrigation from a dam within a district; it is constructed as follows. We weight the effective size of dams (negatively) by their distance to each of the command areas within the district that the drainage course transects, and (positively) by the area of those command areas. These variables are constructed separately for dams in the district and for those (hydraulically) upstream in other districts. Thus, if a district has no dams and no command areas the value of this measure (distNcmda) is zero; if the district has dams but no command areas, it is also zero.

If there are command areas that arenot linkable to any dam then the variable 'otherCmda' is the area of these command areas within the district that are not linked to any dams.

If the district has dams and command areas which dams' drainage transects, then the variable ("distNcmda") is the sum of the distance and command area weighted effective capacity of the dams whose drainage paths transect the command area over all dam/command area combinations within the district.[61] Distance has no effect on the distNcmda variable for dams within the district. For dams that are upstream and intersect command areas within the district, the “distNcmda” values are summed over all the upstream dams; if the district has upstream dams but no transected command areas, distNcmda for upstream dams is zero. Equation 2 details the calculation.

Equation 2 effective size weighted by distance to and command area within t district

$$\sum_{dams_i^d} \sum\nolimits_{cmda_{i,j}^d} \langle es_i * (1-b)^{dist_{cmda_{i.j}^d}} * area_j^d \rangle$$

Where *d* is district, *i* is dam, es_i^d is effective size of dam *i* affecting district *d*; *b* is the negative exponent; $cmda^d_{.i,j}$ are command areas (*j*) in district *d* hydraulically connected to dam_i; *dist* is the hydraulic distance between the dam and command area *j* . Thus, this metric takes account of the size of dams, their distance from areas irrigable from this dam, and the size of these irrigable areas.[62]

Figure 7 illustrates the approach for the Jayakwadi dam completed in the mid-1970s in the mid-Godavari basin. The dam is immediately upstream of a major command area that extends from the district of the dam (Aurangabad, Maharashtra) downstream through several different command areas within Jalna, Bid, Parbhani, Hingoli and districts further downstream (not illustrated). Our measure aims to capture this pattern by using the distance to the command area within the district to negatively weight the potential influence of the dam, and the area of the command area within the district to measure its potential, hopefully, positive effects. **Table *1*** shows the calculation of distance and command area weighted effective size of this dam in each of the districts downstream that its drainage path transects.

[61] The ‘distance to district’ component is set to zero (0) when we use the negative exponential distance function, and to one (1) using the inverse distance function.
[62] Some dams may not command all of a command area, for example if the command area runs across many drainage paths from different dams. It is not likely that the length of drainage through a command area is a good approximation of the proportion of the command area it can command. However, because we weight the effective size by the area of the command area in the district, rather than the whole area of the command area (across all districts and basins where it is located), this may mitigate this distortion.

Figure 7: Jayakwadi Dam and downstream districts in the lower Krishna basin

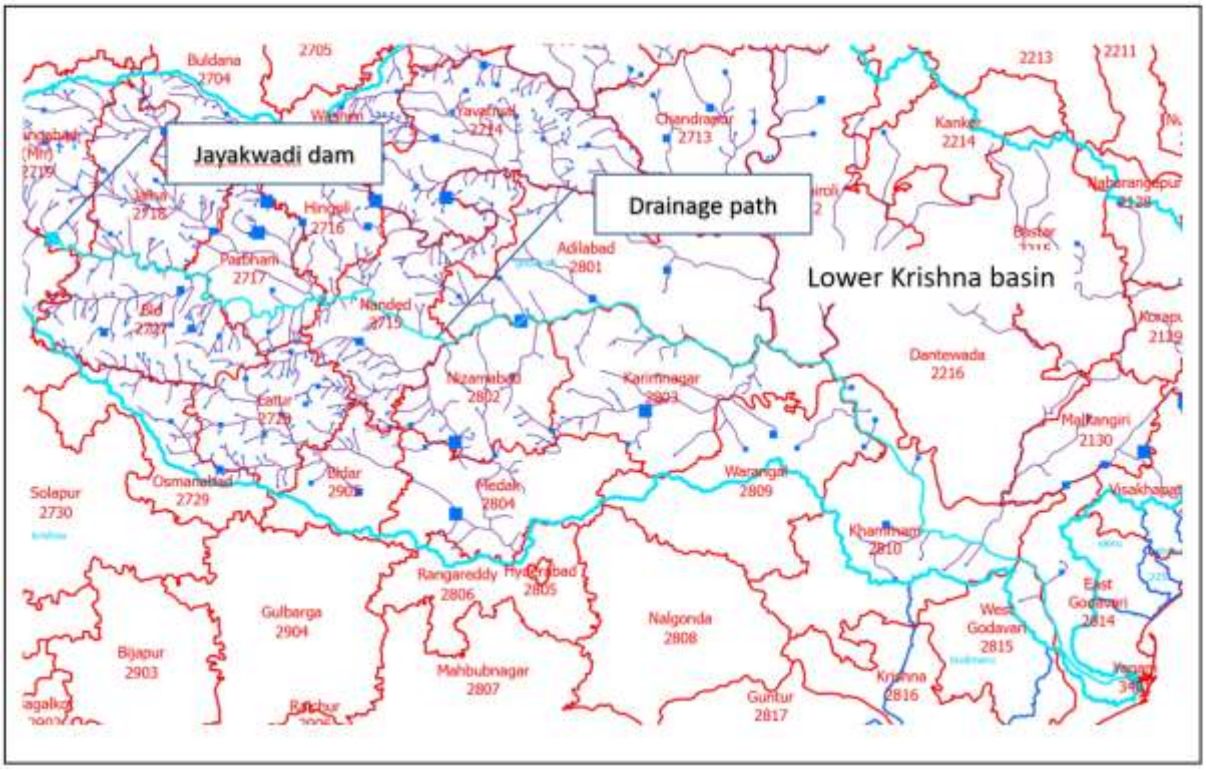


Table 1: Weighted effective capacity of the Jayakwadi dam

District	Capacity $m^3 10^6$	Distance to district (km)	Length within district (km)	Length along border (km)	Weighted effective capacity of dam in district[a, b]
Ahmadnagar	2171	1	0	15.03	1900.00
Aurangabad_(Mh)		1	0	32.93	4100.00
Bid		18	0	166.99	101.82
Jalna		35	0	85.85	26.98
Parbhani		119	91.16	69.55	22.95
Nanded		271	38.81	59.22	5.47
Hingoli		278	17.51	75.39	4.32
Nizamabad		397	0	78.66	2.15
Adilabad		405	24.58	241.45	7.80
Karimnagar		484	1.05	232.18	5.25
Gadchiroli		673	1.84	44.98	0.78
Dantewada		720	1.76	22.63	0.39
Warangal		736	0	52.87	0.78
Khammam		741	163.29	55.06	5.59
West_Godavari		956	0	58.43	0.66
East_Godavari		956	64.7	68.36	2.25
Yanam		1084.56	0	13.7	0.14

a. distance in km divided by 10^2

b. areas km^2

Thus, we assume that the effect of a dam in a command area in a district is related to the effective size of the dam, the (negative exponential of the) minimum hydraulic distance from the dam to the command area within the district, and the area of this command area within this district. For command areas that are transected within districts further downstream, the potential effect of the dam is attenuated by the greater distance of the command area from the dam in the lower districts, but not otherwise by potential diversions of water to these other command areas.[63] The metric we focus on is the negative exponential distance weighted effective size multiplied by the area of the command area (within the district). This number reflects the three most prominent variables likely to determine the effects of a dam – its size, the distance to the command area and the size of the command area. What it leaves out are the timing and extent of development of canals making use of the dams' stored water, and their management.

The areas in the WRIS command areas GIS file that are not hydraulically connected to any dams are added as a second variable,[64] (otherCmda) and are not linked explicitly to dams.[65]

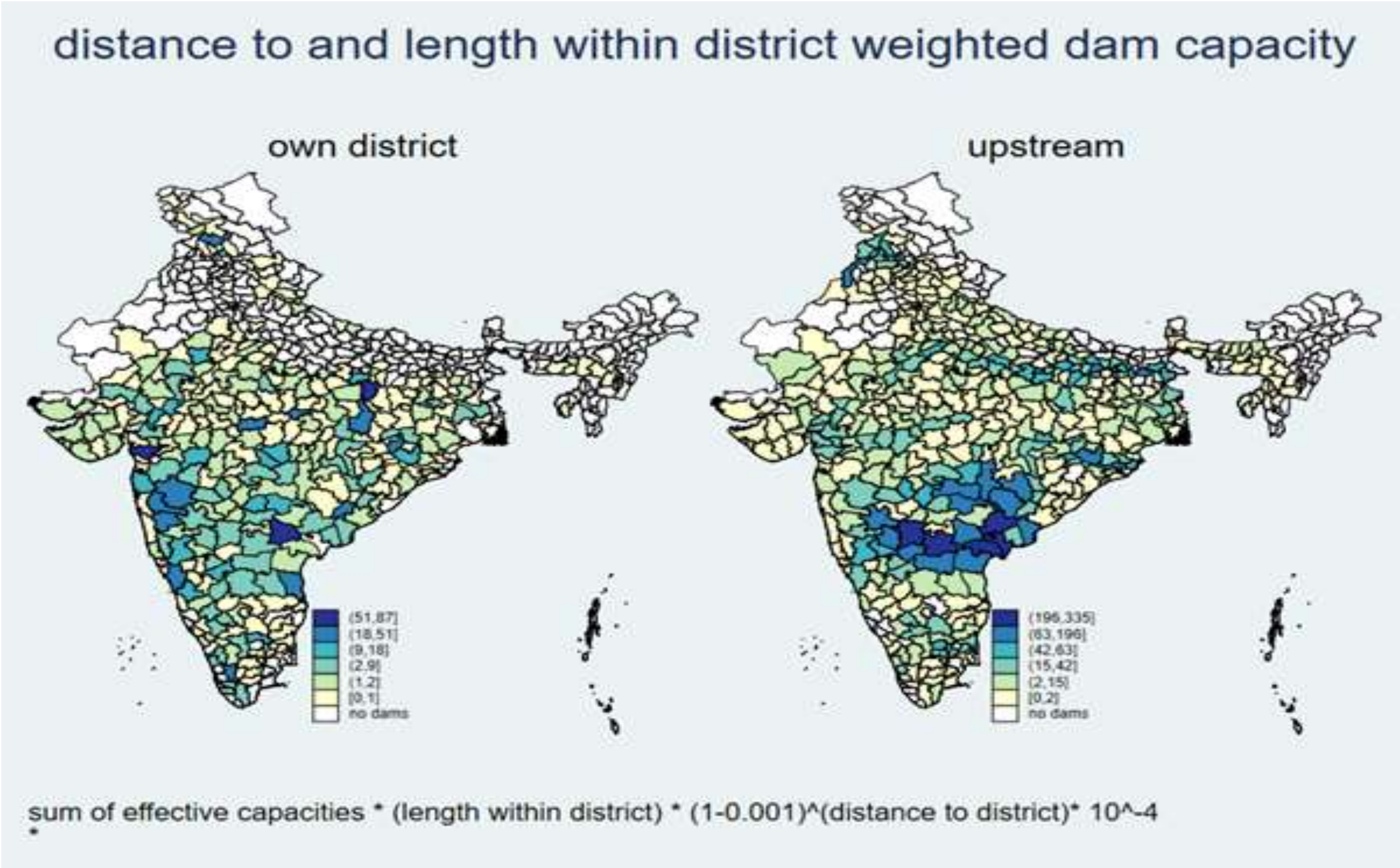
Figure 8 shows the spatial distribution of our "effective capacity weighed by distance and command area" treatment variable reflecting dam size, distance to command area, and command area weighted components for own district and upstream dams.

[63] One can think of further elaborations of this metric which would reflect the amount of diversion of dam water to upstream command areas so that, for example, if the upstream commands were large in relation to the stored water, less would be transmitted further downstream than if the upstream command area was small. This would try to develop a function reflecting diversions of irrigation water rather than distance.

[64] The GIS file has a number of polygons of projects overlapping other polygons; we drop polygons of projects which appear to relate to 'command area development' projects rather than command area irrigation projects.

[65] It would be feasible to connect some of these areas to dams that are known to affect them either manually, or using a GIS file of canal traces. This is important perhaps especially for the large command areas such as those shown in northwest India and other areas irrigated by inter-basin transfers. Other than large command areas in Rajasthan, which can be fed from the interlinking canals from the Indus basin (which convey both run-of-river and dam-stored water through the Bakra-Beas complex system (see Michel, 1967, p 286; Rangachari, 2006, p 35; and many other popular accounts), there are a few other large inter-basin transfer systems that have substantial irrigation components; the Periyar-Vaigai and Parambikulam-Aliyar systems which transfer water from west-flowing rivers to the east-flowing rivers of the Western Ghats, and the Kurnool Cudappah canal which links the Krishna to the Pennar basin. The upstream dams in these systems are not included in our measure of weighted effective dam capacity other than through any other command areas not linked to any dam.

Figure 8: Total effective capacity of dams in districts and upstream weighted by distance and command area



The left hand panel in the **Figure 8** shows that a few districts have (very) high (distance and command area weighted) effective dam capacity. A few districts have large values for effective capacity weighted by distance and command area; Pune, in western India, for example, has many dams and many intersected command areas. Nalgonda, on the other hand, in the lower reaches of the Krishna basin, has few dams, but one dam is very large and several command areas below the dam within the district with which this large dam intersects. Sonbadhra in Bihar has one very large dam (Rihand dam) and several smaller ones upstream of a command area that covers most of the district.[66] These three districts have high values of distance and command area weighted effective capacity of dams within them

Many districts in the Indian Shield have large effective capacities, but their poor soils (low levels of alluvial geology) and dissected terrain mean they have few irrigation command areas, so they have low values of this treatment variable. This suggests that, notwithstanding high effective dam capacity, once this is weighted by the command areas intersected (or not) in these districts the treatment variable low and there may not be much opportunity to make use of the large dams' effective capacity.

The spatial distribution of the effective capacity of dams upstream of districts makes for a more interesting interpretation; districts in the middle of the Krishna basin (Gulbarga, for example) and towards its delta (Nalgonda, Krishna and Guntur districts, and also Karimnagar) at the lower end of the Krishna basin, have extensive command areas and some very large dams within or just upstream, as well as hundreds of other dams further upstream.

Districts along the north- facing slopes of the mid Jamuna (Ganges) basin have many dams upstream in the north facing foothills of the Vindhya range and are covered by command areas (Mirzapur, Allahabad, Kaushambi, Fatehpur, Banda, Hamirpur, Jalaun, Bhind and Agra districts). Districts of the Chambal tributary also have many dams within them and just upstream, and have extensive command areas. Districts in Punjab are widely under command areas and are not far downstream of the mega dams at Bhakra and Pong. When dam size and command area are taken into account, they represent the way very large dams and considerable command areas result in large distance and command area weighted effective size of upstream dams in these districts.

Thus, few districts have very high weighted effective capacity from dams in their own district, and many have only moderate values, because there are few opportunities for irrigation command areas within their own districts; such dams are concentrated in the districts encompassing the watersheds of the major basins in the Deccan plateau (Krishna, Godavari, Narmada and Tapi, Mahi, Cauvery), and in the Himalayan foothills, because such districts provide sites for dams but do not have suitable terrain for irrigation projects.

As noted above, many command areas are not linked to dams by their drainage path, while in reality they may be linked to dams by inter-basin or other canals which transfer water away from the drainage path. These command areas can nevertheless be expected to have

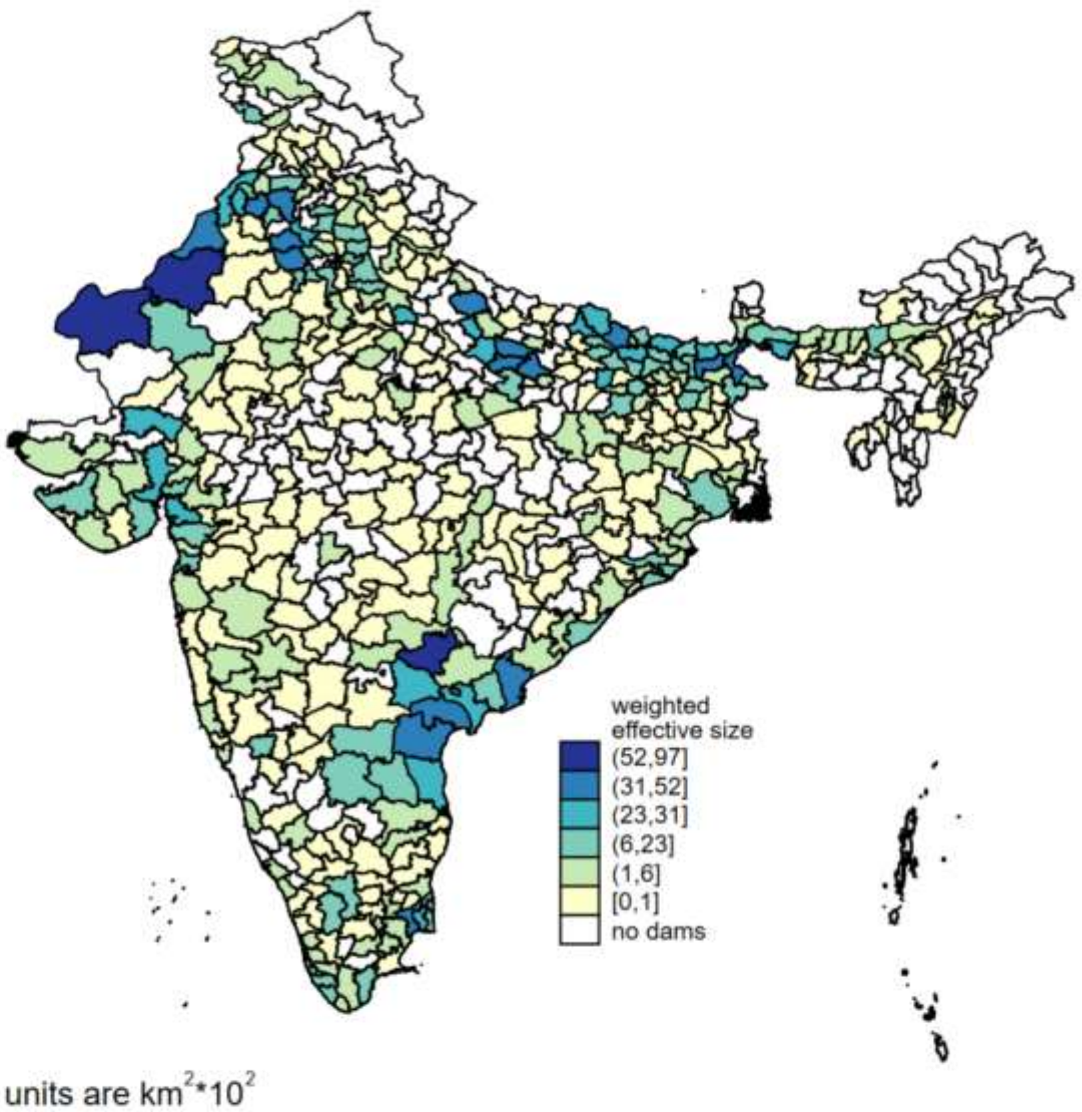
[66] This is somewhat misleading because the command area is in fact a wide-area irrigation development project which did not in fact develop an intense network of canals to irrigate most of the land until the 2000s at the earliest. The Rihand dam has the largest impounded volume among Indian dams.

some impact on agricultural productivity. Bikaner and Jaisalmer in Rajasthan State are examples; the command areas in these districts are fed by the lower Indira Gandhi canal that is itself fed from transfers from dams within India in the Indus basin through the link canals to the Beas and from the Beas by a barrage at Harike Barrage.

Districts with command areas not linked to dams are quite widespread (**Figure 9**). Warangal, made famous by Scarlett Epstein's comparison of wet and dry villages (Epstein, 1962, 1973), is a district widely covered by command areas, but with no dams actually in or upstream of most of them. Guntur and Prakasam have command areas not linked to drainage paths of the Krishna, although they are fed by canals from the Krishna. Districts of north Bihar and Eastern UP towards the Himalaya are widely under command areas, but they are run-of-river schemes not benefiting from water stored in the dam. Districts of the Jaunpur, Sultanpur and Pratapgarh, Barabanki and Sitapur in UP are almost entirely under command areas, but there are no dams in or upstream of them.

This narrative provides insight into the difficulties of linking dams to districts in ways which might reflect dam impacts through irrigation command areas. It is not clear how these metrics might accommodate other ways in which dams might affect districts, for example through altered river flows or groundwater resource availability.

Figure 9: Command areas not linked to dams



4.3.3 A Vegetation Index (VI) of agricultural productivity in districts

We now turn to the third solution required to address the effects of dams using district-level variables: the construction of a balanced panel outcome variable appropriate to the analysis of the effects of dams on agricultural productivity.

In addition to the spatially and temporally biased missing observations in the agricultural production variables analysed in 'Dams', these variables are for only the six "major" crops. These 6 crops account for some 75% of the all-India value of the 18 crops in the WBAg data, which in turn are between 80-90% of the value of the 35 crop total reported in Bhalla and Singh, 2011 (see Appendix 5 for the basis for these approximations). But the most significant lacuna of the use of this 6 crop total is that it does not include pulses and groundnuts, which are often among the 6 crops with highest value of total output in India; groundnut and pulses are of course characteristic of the less abundantly irrigated areas of India, so it is not unexpected that the total value of "other" crops (i.e. not the 6 crops in the agricultural production aggregates in 'Dams') is also spatially biased (see **Appendix 5**).

Our outcome variable needs to be computed so that it addresses two issues; the unbalanced panel, and the fact that it can be computed for areas within districts that are in different river basins and in different irrigation command areas. While we can collapse 'river basins within districts' variables to district level to conduct a district-level analysis, it is the case that dams can only (generally) affect areas of districts within the river basin of the dam. Thus, district level agricultural statistics that are computed for the whole of the district are not appropriate (and, of course, the (extended) WBAg district dataset is unsuitable because it is unbalanced and excludes all districts in several major Indian states, as already argued above).

Two types of outcome data suggest themselves as able to be computed at sub-district levels: remotely sensed data, and VD variables (Meiyappan et al, 2018). Other nationally representative data that can be located within districts have limitations, mainly that the sample sizes are not sufficient to warrant district-level analysis (for example, we explored Demographic and Health Surveys, NSS Consumption and Employment Surveys, and other national-scale surveys such as the India Human Development Surveys (https://ihds.umd.edu/about), the Additional Rural Incomes Survey (ARIS/REDS) and the Rural Economics and Demographic Survey (NCAER, nd)).

Remotely sensed and VD variables have been used in recent studies of the effects of interventions in India. Asher et al (2020) use Vegetation Indexes (VIs) computed from MODIS NDVI variables from 2001–06 (potentially available for each year after 2001 to the present), and 'validate' their VIs using a 'crop suitability' index from the Food and Agriculture Organization, an 'irrigation share' of village area computed from VD variables, a 'predicted consumption' variable using the IHDS-II survey, and a 'District GDP' variable originally computed by the Indian government. These are all proxies for agricultural productivity of questionable relevance (and validity);[67] we use the estimates of agricultural productivity from the district agricultural database reported in Bhalla and Singh (2001, 2012).

[67] There are some initial reasons for caution about these proxies: (1) It is not clear what relevance crop suitability has to actual agricultural productivity; (2) the 'irrigation share' from the Census VDs is computed as area reported as under some form of irrigation divided by total village area – these are likely to be highly unreliable figures, and it is not clear what the total village areas is, as it does not correlate well with area computed by GIS; (3) the

Our VI also differs from that constructed by Asher and Novosad (2019, p 20; see also Asher and Novosad, 2021, Asher et al., 2021) who calculate "the difference between early-season VI (the mean of the first three 16-day composites) and the max VI value observed at the village level (Labus et al, 2002; Rasmussen, 1997), mean VI (Mkhabela et al, 2005), and cumulative NDVI (Rojas, 2007) (the sum of NDVI from each of the nine composites during the growing season)".

In constructing their VIs Asher and Novosad "prefer the differenced measure because it effectively controls for non-crop vegetation (such as forest cover) by measuring the change in vegetation from the planting period (when land is fallow) to the moment of peak vegetation" (2019, p 20).

This measure using fixed beginning-and-end-of-seasons for all of India, and including negative values of NDVI, is not suitable to assess the impact of dams on agricultural productivity. Different regions of India have different agricultural (and climatic) seasons, and begin and end their seasons at different times, including the main monsoon *kharif* season.[68] Irrigation enables and or enhances agricultural productivity in all seasons, perhaps especially outside the main *kharif* season. Measures which include only the period from mid-May to mid-October for each year do not correspond well to India's agro-climatic conditions.

Furthermore, it is transparently not the case that this measure will control for deciduous forestry, where leaves fall in the autumn and reappear in spring, quite closely corresponding to the main monsoon period. It is highly likely that the Asher and Novosad, measure captures forest as well as agricultural growth (this conjecture is supported by maps of their measure, which show high values in forested areas; details available from the corresponding author).

Instead of the MODIS/NDVI/EVI variables used in Asher and Novosd, we use an NDVI data series (described by Tucker et al, 2005), which covers 24 two-week periods in each year from August 1981–July 2011. This is a more suitable time period to assess the effects of the large growth in numbers and total effective size of dams in India from the 1970s through to the 1990s. (It is also closer to the time period used in 'Dams' – 1971–99 – especially if we were to allow for lags between dam completion and their effects.)

Our VI is computed by taking the sum of positive changes of values of raster pixels (conditional on being >= 0) between one image and the next, and summing the resulting

'predicted consumption' variable is also not a close measure of agricultural productivity, even if (especially rural) consumption mainly reflects agricultural activities, as it will include many non-agricultural factors; (4) the 'District GDP' figures are highly constructed and have subsequently been withdrawn.

68 The standard texts of the geography of south Asia make it clear that the 'normal' onset dates of the southwest monsoon range from late May in the southeast of India to late July in the northwest; the retreats range from early/mid-September in the north to late November in the south. See https://www.britanica.com/science/Indian-monsoon, accessed: 10 February 2022. There is considerable variation in the onset and retreat from year to year, and location to location. Various remotely sensed products report these and other dimensions of each monsoon (e.g. MODIS3C1). Using the same period for all of India, or the same dates of onset and retreat for each year, or the VI of a single season when there is multiple cropping, will miss a lot of information. The spatial distribution of the Asher & Novosad NDVI/EVI variables are quite different from our AVHRR based VI, and the justification for the 'preferred' (difference – ndvi_k, evi_k) measure seems to be *a priori*. As noted above, Asher & Novosad, provide several other NDVI measures (delta, mean, cumulative, max) but do not explain whether they assessed these measures, which arguably have claims to represent agricultural productivity. These other measures, and our own measure, give different spatial and temporal distributions; details can be obtained from the corresponding author.

values over all 24 periods in a year. We only use NDVI pixels that correspond to crop or potential crop areas, as represented by land use values 2, 7, 8, 10, 14,[69] in the 1985, 1995 and 2005 Land Use images (Roy et al, 2016)[70]. This approach respects the restriction of the impacts of dams to cultivable land (rather than forestry, water bodies, or rocky, desert or otherwise uncultivable lands) and the variable timing of both the onset and the retreat of the main monsoon over locations (earlier and later, respectively, in the south compared to the north) and the variation in these dates from year to year. Negative NDVI values are thought to reflect water bodies and so should not be included in calculations of biological (agricultural) productivity. We compute the annual total of NDVI of pixels corresponding to croppable land for comparison but see no merit in presenting analyses of this variable, avoiding possible data mining[71].

We validate our VI against VD variables,[72] and also the district agricultural productivity variables in Bhalla and Singh (2012).[73] Statistics can be computed for these annual NDVI pixels within any level of administrative area (villages, different sets of districts such as the different Indian censuses, SHRUG super-districts, Bhalla and Singh districts, World Bank Agriculture districts, and so on), for use as proxies for agricultural productivity (mean, median). More details of our construction and validation of our VI are available on request.[74]

4.4 Addressing the endogeneity of dams – geology and dam placement

Finally, to address endogeneity, we argue that a plausible criterion for the location of dams lies in the need for strong and impermeable geological formations, required for the foundations and sides (abutments) of dams and to limit seepage of stored water (Golze, 1977, p 7).[75]

We construct variables reflecting the underlying geological structures of the Indian subcontinent, reported in a 'geology' shape file,[76] by combining the main lithological series into seven categories which are mapped in Figure 10. As the overlay of locations of dams

[69] 1) Deciduous Broadleaf Forest; 2) Cropland; 3) Built-up Land; 4) Mixed Forest: 5) Shrubland; 6) Barren Land; 7) Fallow Land; 8) Wasteland; 9) Water Bodies; 10) Plantations; 11) Aquaculture; 12) Mangrove Forest; 13) Salt Pan; 14) Grassland; 15) Evergreen Broadleaf Forest; 16) Deciduous Needleleaf Forest; 17) Permanent Wetlands; 18) Snow & Ice; 19) Evergreen Needleleaf Forest. See Meiyappan et al (2018). Data available at http://dx.doi.org/10.3334/ORNLDAAC/1336. Accessed: February 2022.

[70] 1985 for AVHRR years 1981–99, 1995 for years 1990–99 and 2005 for years 2000–10)

[71] We also calculated the Asher and Novosd VI but can see no point in presenting any results, again avoiding possible data mining and HARKing (Kerr, 1998).

[72] Unfortunately, to date we only have access to the 2001 Indian Census VD, rather than the panel available to Asher and Novosad (2019). Nevertheless, we are confident our VI performs significantly better as a proxy for agricultural productivity.

[73] We do not use 'night lights' RS variables because the more recent series seems largely irrelevant to agriculture and the earlier series has significant consistency and spatial precision issues (Gibson et al, 2020).

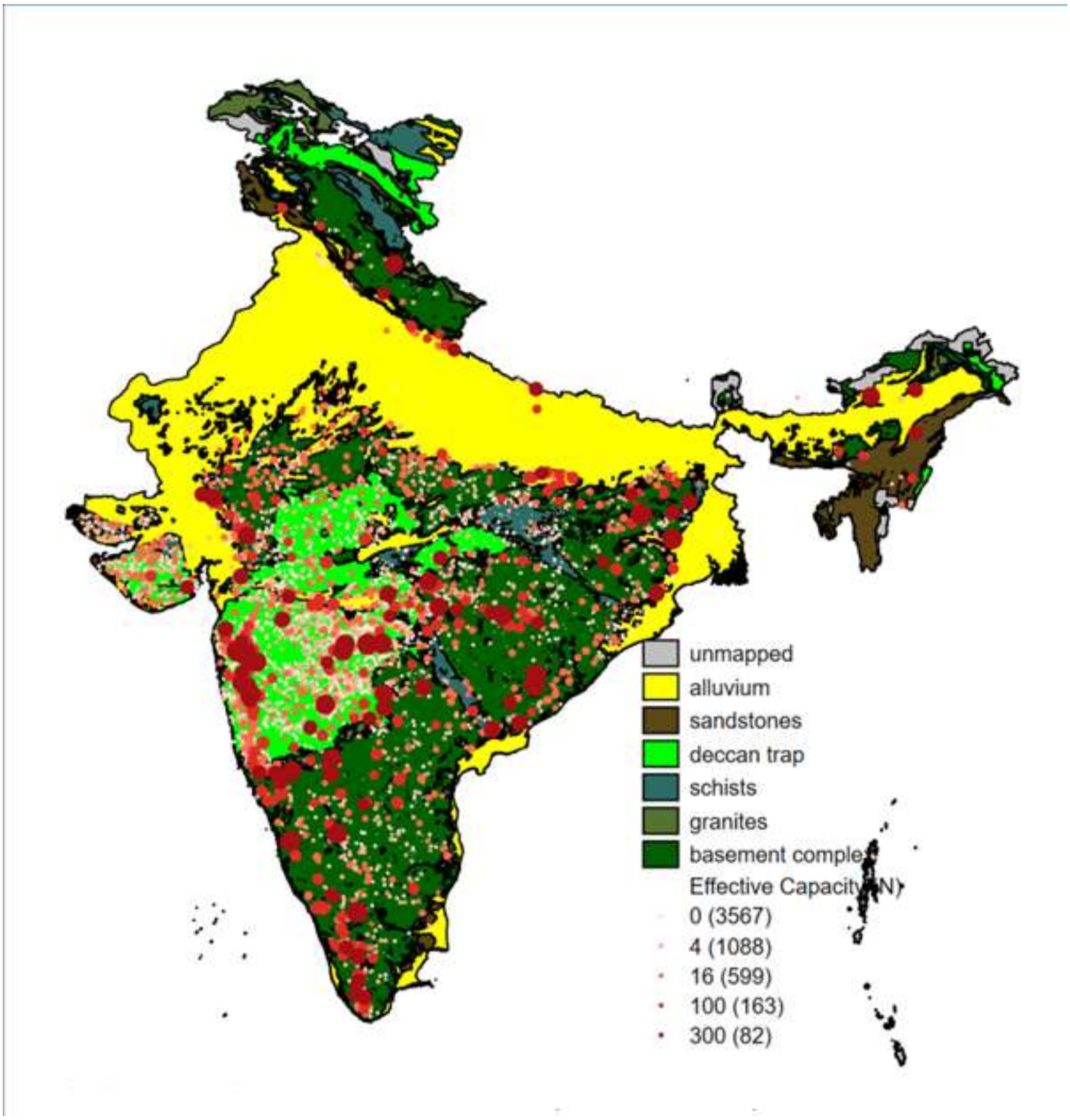
[74] Two other variables are likely to be important in determining agricultural productivity: groundwater and agro-climatic conditions. Groundwater is crucial to irrigation in India both as the primary source of irrigation and to supplement canal irrigation Shah, 2009. The prevalence of groundwater resources is highly collinear with the prevalence of alluvial geology. Agro-climatic zones combine soil and climate variables and are important determinants of agricultural potential; they are strongly associated with both agricultural production, growth and poverty reduction in India (Palmer-Jones & Sen, 2003). Because groundwater is highly collinear with geology, and for reasons of space and time, the proportions of different AEZs in districts are not discussed further here.

[75] "Obviously, a site should be in a narrow section of a stream channel and where both abutments have sufficient height for the need. The foundations, including abutments should be of rock or consolidated materials sufficiently strong to support the structure and they must be watertight or nearly so that excess leakage can be prevented by sealing."

[76] Geology_2M.zip downloaded from Geological Survey of India, 11 March 2021.

shows, very few are constructed in areas of alluvial geology and almost all are constructed in what can be termed the Indian Shield, comprising the Deccan Basalt and various structures (cratons) of peninsular India (Sharma, 2009) south of the Indo-Gangetic plains, or in the western Himalayan foothills.[77] These variables are of course collinear with topography variables, but not with each other, except for a negative relation between the shares of alluvial and the various geological formations of the Shield, and between the Deccan Trap and sandstone and basement complex structures (see **Table 3, Appendix 1**: Additional tables).

Figure 10: Geology and placement of dams



[77] The 'supergroup' geology variable in the geology file was reclassified, with values 0–199 'unmapped', 2–299 'alluvium', 300–399 'sandstone', 400–499 'Deccan Trap', 500–799 'schists', 800–899 'granites' and 900–999 'basement complex'.

Sources: Geology – WRIS geology 2m, dams – NRLD, 2019

The association of dams with the geologies of the Indian Shield plainly visible in **Figure 10** is confirmed in Table 2 in both cross-section and panel regressions (mimicking 'Dams' Table II).[78] The Variable Inflation Factor (VIF) statistics are acceptable except for the district-area and river length variables, which are highly collinear; the use of both rather than only one of these variables is unobjectionable as they both reflect the extent of the district. Growth of numbers of dams completed in the period 1971 to 1999 is also negatively associated with the proportion of alluvial geology, but the coefficient on alluvial geology with (the number of) upstream dams (in column 13) is not significant.[79]

[78] The 'predicted state dams' variable is the annual total of dams completed in India multiplied by the proportion of all dams completed in the state up to 1970 relative to the total number of dams completed in India up to that year.

[79] This somewhat surprising result warrants further analysis; it may be the result of the bimodal distribution of dams upstream by proportion of alluvial geology.

Table 2: Dam placement (numbers of dams) and geology

		Cross section 1999								Panel 1971–99				
	Inter-	Dams		Upstream		Dams		Upstream		Inter-	Dams	Upstream	Dams	Upstream
	acted	b/se	vif	b/se	vif	b/se	vif	b/se	vif	acted	b/se	b/se	b/se	b/se
		1	2	3	4	5	6	7	8	9	10	11	12	13
Sandstone	N	3.85	[3.50]	-17.84	[3.50]					Y	-0.04	0.17		
		(2.37)		(18.40)							(0.03)	(0.77)		
Basement_complex	N	4.67**	[3.53]	-73.52**	[3.53]					Y	0.01	-0.06		
		(2.16)		(34.39)							(0.01)	(0.08)		
Deccan_trap	N	15.35**	[3.46]	-58.22	[3.46]					Y	0.04***	-0.05		
		(7.25)		(40.67)							(0.01)	(0.10)		
Granites	N	-6.59	[1.44]	19.01	[1.44]					Y	-0.07	1.81		
		(6.48)		(89.52)							(0.07)	(2.27)		
Schists	N	20.48***	[1.40]	107.24	[1.40]					Y	0.06***	0.22		
		(6.87)		(168.74)							(0.02)	(0.20)		
Alluvium	N					-5.83**	[3.92]	65.29**	[3.92]	Y			-0.03***	0.06
						(2.19)		(24.98)					(0.01)	(0.08)
km2		0.00***	[39.00]	0.02**	[39.00]	0.00**	[38.59]	0.02**	[38.59]	Y	0.00**	0.00	0.00***	0.00
		(0.00)		(0.01)		(0.00)		(0.01)			(0.00)	(0.00)	(0.00)	(0.00)
rverkm		-0.01***	[34.55]	-0.10**	[34.55]	-0.01**	[34.11]	-0.09*	[34.11]	Y	-0.00	-0.00	-0.00	-0.00
		(0.00)		(0.04)		(0.01)		(0.04)			(0.00)	(0.00)	(0.00)	(0.00)
N		589		589		589		589		y	17081	17081	17081	17081
r2		0.704		0.267		0.678		0.259			0.753	0.387	0.723	0.383
Spec		x-section		x-section		x-section		x-section			panel	panel	panel	panel
Fe		state		state		state		state			state*year	state*year	state*year	state*year

Notes: This table mimics 'Dams' Table II, columns 1 and 3. 2001 districts.* p<.1, ** p<.05, *** p<.01.
km2 and river km are the area and length of river of the district
Upstream dams include ALL dams hydraulically upstream, not just those in neighbouring districts that are upstream.
'Interacted' means that the topography and geography variables (unchanging variables that would be dropped in panel regression otherwise) are multiplied by v 'predicted state dams variable'.

4.4.1 Correlates of the weighted effective dam capacity of districts

Clearly, geology plays a meaningful role in the location of dams; the geology of the Indian Shield has many potential dam sites because of its strong rock formations, and of the way rivers have carved narrow courses. Equally clearly, districts with a predominance of alluvial geology are unlikely to have dams, but many have many dams upstream completed by 1999 (including over the period 1971–99). These characteristics meet the 'external' criterion for being an instrument[80]; however, the more relevant question is whether the geology of a district is associated with effective (weighted) dam capacity. It is not, except that districts with alluvial geology have very little effective dam capacity within them, but much upstream.

The distance and command area weighted effective capacity of dams in a district is not closely associated with the topography variables used in 'Dams' (see **Table *3***, columns 1). This measure of effective dam capacity is also not well explained by geology either (**Table 3**, column 3), in part because the districts in the Indian Craton are not conducive to command areas, lacking extensive alluvial geology. Effective capacity upstream is negatively related to higher elevations (column 3) and to basement complex and schist districts (column 4), because these areas are not suitable for command areas but have upstream dams. Upstream effective capacity is positively related to the proportion of alluvial soils (column 6), notwithstanding the many such districts, typically low in the Ganges basin, that have command areas but the dams that intersect their command areas are far distant, or these alluvium abundant districts have no upstream dams even though they have command areas (typically, districts of the lower region of the north side of the Ganges Basin).

[80] As we show below geology is very unlikely to meet the "exogeneity" criterion.

Table 3: Cross-section (OLS) geography correlates of effective capacity of dam distance and command area weighted (1999)

	Distance and command area weights					
	Own district	Upstream	Own district	Upstream	Own district	Upstream
	1	2	3	4	5	6
sriver2_rpj	-21.89	10.04				
	(21.54)	(10.68)				
sriver3_rpj	-22.76	22.78				
	(23.24)	(18.91)				
sriver6_rpj	-21.66	19.60				
	(20.42)	(12.88)				
elev2_rpj	1.67	-0.07				
	(1.28)	(2.24)				
elev3_rpj	-0.11	-5.45*				
	(0.55)	(2.90)				
elev4_rpj	2.16	-0.77				
	(1.64)	(2.25)				
sdistrict2_rpj	19.20	-6.85				
	(18.90)	(10.82)				
sdistrict3_rpj	28.71	-14.43				
	(28.21)	(15.90)				
sdistrict6_rpj	17.47	-20.93				
	(17.48)	(14.69)				
basement_complex			1.42	-3.48*		
			(1.36)	(1.93)		
deccan_trap			0.90	-1.86		
			(0.80)	(1.79)		
granites			-0.33	16.86		
			(0.52)	(18.24)		
sandstone			0.64	-0.13		
			(0.63)	(0.99)		
schists			1.09	-5.99*		
			(1.18)	(2.99)		
alluvium					-1.19	2.77*
					(1.17)	(1.54)
R-squared	0.096	0.222	0.051	0.208	0.049	0.199
N	589	589	589	589	589	589
spec	x-section	x-section	x-section	x-section	x-section	x-section
fe	state	state	state	State	state	State

In the panel analysis (**Table *4***) the effective weighted capacity of own district dams (column 1) shows some statistically meaningful (at 0.1%) growth only in districts with higher proportions of moderate elevations, but the association is weak. On the other hand, geology variables show a strong association with effective weighted dam capacity; basement complex, Deccan plateau and sandstone geologies, which are strongly negatively associated with growth in distance and command area weighted capacity (column 3); granites and schists are positively associated with this measure of effective dam capacity but the areas of these two categories of geology comprise small proportions of districts which have some alluvial areas (**Figure 10**)

In terms of the effective weighted capacity of upstream dams the associations with the topography variables (Table 3, column 2) are confounded by collinearity. On the other hand, the geology variables are (unconfounded) strong predictors of this variable and clearly meet the ‘external’ and unconfounded criterion for IVs. However, because of the negative association of the proportions of Indian Shield geologies in districts with alluvial geologies and the strong association of alluvial geologies with irrigation and agricultural growth, these variables cannot possibly meet the exclusion criterion. Therefore we do not employ instrumental variables estimators; instead we use the population averaged estimator of the panel regression suite in Stata (Stata, 2021) as recommended by Cameron and Miller, 2016).

Table 4: Panel geography correlates of distance and command area weighted effective capacity (1971–99)

Dams in	Topography		Geology		Alluvium	
	Own district	Upstream	Own district	Upstream	Own district	Upstream
	1	2	3	4	5	6
dss_sriver2_rpj	-31.32	26.94				
	(61.08)	(19.37)				
dss_sriver3_rpj	-56.39	49.18**				
	(66.96)	(21.25)				
dss_sriver6_rpj	-86.28	5.16				
	(66.53)	(21.10)				
dss_elev2_rpj	4.71*	-0.44				
	(2.53)	(0.80)				
dss_elev3_rpj	2.74	-8.55***				
	(3.01)	(0.96)				
dss_elev4_rpj	24.74	-4.87				
	(41.81)	(13.28)				
dss_sdistrict2_rpj	27.11	-25.50				
	(61.09)	(19.38)				
dss_sdistrict3_rpj	26.41	-41.15**				
	(65.36)	(20.73)				
dss_sdistrict6_rpj	67.57	-35.11*				
	(61.74)	(19.59)				
dss_basement_complex			-5.51**	-3.63***		
			(2.30)	(0.73)		
dss_deccan_trap			-4.72**	-4.94***		
			(2.05)	(0.65)		
dss_granites			165.27**	447.67***		
			(70.36)	(22.28)		
dss_sandstone			-26.02	-29.44***		
			(30.40)	(9.64)		
dss_schists			15.88**	-2.88		
			(6.76)	(2.14)		
dss_alluvium					2.53	3.47***
					(2.38)	(0.77)
R-squared						
N	17081	1708	17081	17081	17081	17081
spec	pa cor(ar2)	pa cor(ar 2)	pa cor(ar 2)	pa cor(ar 2)	pa cor(ar 2)	pa cor(ar 2)
fe	state*year	state*year	state*year	state*year	state*year	state*year

*Note: the dependent variable is effective capacities of dams; variables are es*cmda*(1-0.001)$^{(distance\ to\ cmda)}$ scaled by $10^{-1,}$ 10^{-2}.*

The main limitation of these data is that, while we know when dams were completed, we do not know when command areas were developed. While we can use the date of completion of the linked dams to create panel data (district * year), we do not know the trajectory of effects that actually occurred since, in many cases, canal command development and farmers' take-up certainly lagged considerably on dam completion.[81]

4.4.2 Agricultural productivity growth and effective capacity of dams in and upstream of Indian districts

Here we regress our VI proxy for agricultural productivity on measures of dam capacity described above and add covariates which might confound the relationship, in the absence of an IV strategy. We run the regressions in cross section for 1999, and with the panel 1981–99,[82] for various measures of dam capacity – numbers of dams, the sum of effective sizes of dams, and the distance and length, and distance and command area weighted effective capacities.

Table 5 presents the results for all our hypothesised weighted metrics of effective capacities of dams in and upstream of districts.[83] All measures start with the effective capacity of dams. The first weighted measure takes account only of the distance from the dam to the district. The second includes distance to the district and a measure of the potential effect within the district proxied by the length of river course from the dam within or along the border of the district (we distinguish between these two lengths here). The third measure uses the area of command areas intersected by the drainage course as a proxy for effects within the district.

The first and second measures show no statistically meaningful relation between effective dam capacity and our VI. However, when the potential effect of dams is proxied by the area of command areas with which its drainage course intersects, there is a positive and statistically significant association between the growth of weighted effective dam capacity and our VI measure of agricultural productivity. This shows clearly that only when taking account of irrigation command areas is there a plausible, statistically significant relation between dams and their effects, and then only for dams upstream rather than dams in their own districts.

This finding fails to support the finding in 'Dams' that districts have negative effects in their own districts but does find that the distance and command areas weighted effective capacity of dams 'upstream' are positively related to our VI measure of agricultural productivity. These results take account of plausible geography controls but do not warrant strong causal claims, as there may be other factors accounting for the positive association of effective weighted dam capacity of dams upstream with our VI measure of agricultural productivity.

[81] A common trajectory is of irrigation command areas needing to start 'rehabilitation' (often associated in India with irrigation management transfer to Water Users Associations) almost as soon as, if not before, their completion.

[82] Our VI only begins in 1981. It may be appropriate to use lagged dam variables in later work because of the likely delays between dam completion and their effects on agricultural productivity. These lags may be non-linear as irrigation command areas get developed slowly over time and farmers take time to adjust to the new or enhanced water resources available to them. Negative effects may also occur, perhaps because of waterlogging or salinity, which also may only appear over time.

[83] There is no merit in reporting regressions of numbers of dams in and upstream of districts, for the reasons explained above. Any such regressions are likely to report spurious associations, reflecting the influence of uncontrolled variables affecting location of the many small (large) dams, which are unlikely to have much discernible effect at district level.

Table 5: The AVHRR VI and distance and command area weighted effective capacity of dams (panel)

Dependent variable		avhrr ndvi					
		Sum of effective capacities weighted by negative exponential distance and:					
Predictors		distance only	length within	command area	distance only	length within	command area
		1	2	3	4	5	6
Distance to district	own district	-0.87			-0.99		
		(2.14)			(2.14)		
	upstream	0.83			0.58		
		(0.75)			(0.75)		
Distance to and length within district	own district		-3.30			-3.80	
			(4.07)			(4.07)	
	upstream		-1.02			-1.49	
			(1.43)			(1.44)	
Distance and command area	own district			1.31			3.54
				(30.78)			(30.78)
	upstream			15.20**			13.14*
				(7.18)			(7.21)
Predicted state dams interacted with	prop alluvium				1.78***	1.89***	1.73***
					(0.58)	(0.58)	(0.58)
	other cmdas	0.00	0.00	0.00	0.00	0.00	0.00
		(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
	area (km2)	0.00	0.00	0.00	0.00***	0.00***	0.00***
		(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
	river length (km)	-0.00*	-0.00*	-0.00*	-0.00***	-0.00***	-0.00***
		(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
R-squared		0.944	0.944	0.944	0.944	0.944	0.944
N		11210	11210	11210	11191	11191	11191
spec		pa cor(ar 2)	pa cor(ar 2)	pa cor(ar 2)	pa cor(ar 2)	pa cor(ar 2)	pa cor(ar 2)
fe		state*year	state*year	state*year	state*year	state*year	state*year

Notes: Cells are b/se . 'pa' estimations are “xtreg y x…… ,., pa cor(ar 2); r2 is computed as the square of the correlation of the predicted and actual dependent variable.
Estimation period: 1971–99. Distance and length weights are es*length*[(1 - 0.01)^km^2]; distance and command area effective capacity is es*[(1 - 0.01)^km^2] * [cmda area in district].
p< .1 * p< .05 ** p< .01 ***

The finding of no obvious (negative) association of agricultural productivity in the district of the dam of the distance and command areas weighted effective capacity of dams variable does not mean that dams do not have effects in their own districts. Nevertheless, it striking that when account is taken of the effective size of dams, which is associated with the area of the impounded reservoir and therefore the area of land removed from previous or uses, and the command areas that can be linked to dams in their own districts, no net association with our VI proxy for agricultural production is found in our estimations. It could be that other outcome variables might have associations with our measure of dams, but that requires further investigation. As noted below, the negative association reported in ‘Dams’, is likely due to the use of numbers of dams as the treatment variable, and at least partial failure to control for disadvantageous characteristics of districts with many dams.

None of the empirical approaches using districts suggested and estimated above reflects fully the realities of links between dams and the areas they are likely to affect. Using numbers of dams in districts and their upstream neighbours does not correspond to any sort of meaningful, quantifiable hydraulic link between dams and districts, even when implemented with correct identification of neighbours and their (up/down/neither/both) category. Further, such approaches ignore the crucial economies of scale in actually existing dams. The estimates in ‘Dams’ are further flawed by errors in the construction of data, and are not improved by and estimator (FGLS) – which seem to have been misapplied[84] – which we have not been able to replicate, and for which no code is available.

Constructing a treatment variable for dams from the size of dams, hydraulic distances to and length of river/drainage path within districts shows no credible effects of dams among the regression coefficients using basic estimators and correctly computed data; however, a factor that is credible in the sense that there are good reasons to believe it will affect the effects of dams in districts – the proportion of alluvial geology and area under irrigation commands – is statistically significant when included in estimations.

While clearly in principle irrigated areas can be linked to dams, in practice this is difficult thanks to a lack of data on the timing of the construction and first operation location of canals and their use (management). Attempting to create a variable which takes account of this linkage, we created district-level variables reflecting the size of, distance to, and irrigable command areas hydraulically connected to dams. This distance and command area weighted effective capacity of dams upstream is positively and convincingly related to our proxy for agricultural productivity. When we added an additional variable of the area of command areas within the district which could not be linked to dams by our methods, and the proportion of districts under alluvial geology, this conclusion remained, although with reduced statistical significance.

5 Whereof one cannot speak, thereof must one remain silent?

How could a study of the effects of dams which failed to take account of their size and with the manifold and plainly visible flaws in key data and econometrics of ‘Dams’ have been largely unchallenged for nearly two decades?[85] The answer is evidently ‘because it could’, but that raises more questions than can be addressed here (see Camfield et al, 2014).

Our initial approach addressing some of the conceptual, data and econometric problems uncovered in ‘Dams’ required that we reconstruct the obviously faulty data and unclear estimation methods, and construct new variables of dams, environment, and outcomes, and credible connections between dams and districts. We construct a new variable reflecting agricultural productivity, in part because of the flaws in the augmented WBAg dataset,[86] notwithstanding its continuing quite widespread appearance in the academic literature.[87]

Instead we use the AVHRR VI variable described above; this produces results which suggest no relation between dams and outcomes in either their own districts, or in downstream districts ***unless*** account is taken of the development of irrigation capacity in

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[84] Both the number of observations and code we have seen suggest that the estimator used in ‘Dams’ violated the requirement that the panel data used are strongly balanced.

[85] Or, indeed, published in a high profile economics journal in the first place?

[86] Among other limitations, even the WBAg balanced panel does not include all important states; it excludes the major states of Himachal Pradesh, Jammu and Kashmir, Kerala and Assam.

[87] e.g. Dincecco et al (2022). We also use these data (Iversen et al, 2013), but only in relation to a critique of work by others (Bannerjee & Iyer, 2005) in which it was used. In other work on related topics we used the agricultural economy data from Bhalla and Singh, 2001 (Palmer-Jones & Sen, 2003). Further discussion of the WBAg data set appears in **Appendix 5**.

downstream districts. We reject the use of variables for neigbouring districts as there is no scientifically literate reason for doing so. Our results also suggest that districts which had more dams, and had more dams completed between 1971 and 1999, are likely to be systematically disadvantaged in relation to, say, districts with many upstream dams, in that dams with many districts tend to be in regions which lack the alluvial geology more suitable for irrigation (especially in association with the more abundant groundwater resources of such areas).

Once we have a correct set of topographical and other data and have dispersed the fog of mysterious and confusing estimation procedures, we can draw some conclusions about the effects of large dams in India. The conclusions of 'Dams', that dams had negative effects in their own districts, is probably confounded by the disadvantageous environment and economies of these districts which the IV method does not resolve. The conclusion that districts benefited from dams in their upstream neighbours, derived using faulty data and variable construction and questionable econometrics, which are not readily reproduceable, is more appropriately framed as 'districts with much upstream dam capacity, that have large areas that are suitable, and have been developed, for irrigation, together with other supportive infrastructure (electricity, roads, towns maybe), appear to have experienced more rapid growth of agricultural productivity', which is not the same thing at all.

The conclusions drawn from the very similar estimation approach to that used in 'Dams', by Strobl and Stobl 2010, for sub-Saharan Africa, and those drawn by Blanc and Strobl, 2014 for South Africa, may need also to be modified in the light of the doubts about whether the estimation methods adequately control for confounding variables and uses an appropriate variable representing dams. S&S similarly used numbers of dams rather than (effective distance and command area weighted) dam capacity[88], and the same river and unit slope and elevation variables to control potential confounding by unobserved contextual factors. As argued in **Appendix 2**, the Pfaffstetter units used in S&S suffer the same issues of what and what type of areas dams actually affect in their own or downstream neighbouring units (however defined). Although S&S presumably avoid the egregious errors in constructing (merging) river variables, and neighbour identification and categorisation[89] errors, which we find in 'Dams'; and used appropriately their (well known) estimator, they are unlikely to have adequately controlled other confounding factors.[90]

Further work may allow us to address whether these conclusions hold for other outcome variables, especially poverty, but panel district-level poverty data require their own careful (re)construction, and it is not clear yet that the data used in 'Dams' is sufficiently robust for this purpose, given the problems we uncovered with the agriculture and census data

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[88] Blanc and Strobl, 2014, compare large and small dams; but this only draws attention to the issue rather than providing an appropriate way to estimate their effects. While noting the need for irrigation to benefit from dams, Blanc & Strobl retain the use of Pfaffstetter units of analysis and the numbers of small and large dams rather than their effective capacities. There is no measure of the actual intersection of upstream dams with irrigated or irrigable areas. The construction of variables in Blanc & Strobl is unclear for the same reasons as we suggest is the case in S&S – which 6-digit hydrological units are considered upstream or neighbours, and their neighbour types.

[89] It is unclear how S&S categorise neighbouring Pfaffstetter units; as shown in Appendix 2 the numbering sequence of these units does not provide much information about the proportion of the dams' own unit or their neighbours could actually be affected by a dam in a higher numbered unit.

[90] Nor will the S&S estimation have mitigated any endogeneity of dam capacity placement, although it seems unlikely that this is more of a problem in the domain they address than in India.

deployed by the authors, and controversies over poverty statistics in India (Deaton & Kozel, 2005[91]).

It is unlikely that the parameters we have estimated can be sensibly used to make cost–benefit calculations for new dams, even taking account of dams' capacities and new and existing irrigation potential downstream, as the outcome variable is a Vegetation Index and not a more direct measure of agricultural production that could be given a monetary value. That there is a positive relation between upstream dams and presumably beneficial agricultural production and productivity outcomes in districts downstream with existing irrigation schemes that can be hydraulically connected to the dam is likely to be a useful reminder that dams are unlikely to be of much (agricultural) benefit by themselves. The suggestion that dams have widespread negative effects in the districts in which they are constructed[92] is not supported by our work, but clearly could be investigated further. Applications of tools from the "credibility revolution" in applied economics even with highly credible credentials clearly cannot be taken at face value, at least when applied to the impacts of large dams.

[91] See Sinha and Roy, 2022, for a recent discussion. The poverty variables used in 'Dams' are largely drawn from Topalova, 2007. The poverty variables for all except 1973 are from Topalova whose PhD thesis on the same topic, was supervised in the same department and at the same time as the work on 'Dams' was being conducted. At best these variables (rural head count, poverty gap, and gini coefficient), will have wide confidence intervals due to the low sampling rates at district level in the underlying National Sample Survey (NSS) Consumer Expenditure Survey (CES) and Employment and Unemployment (EUS) data sets. The construction of these variables in Topalova (2007, 2010) is not fully explicit but, surprisingly, apparently uses the expenditure variable from the EUS rather than the CES (Topalova, 2010: 8). Dubey and Palmer-Jones, 2005a, b & c, provide our views on utility of poverty statistics in India from these surveys for making comparisons over space and time for India.

[92] This is not to suggest that there are no negative effects in districts where dams are constructed, as there clearly are some; it is only to assert that there is no evidence of such an effect on agricultural production in our analysis, and the analysis in 'Dams' is unreliable and does not warrant being used to support such a conclusion.

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Appendixes

Appendix 1: Additional tables

Appendix 1 Table 1: ‘Dams’ Table III (copied verbatim)

Table III

Dams and Agriculture

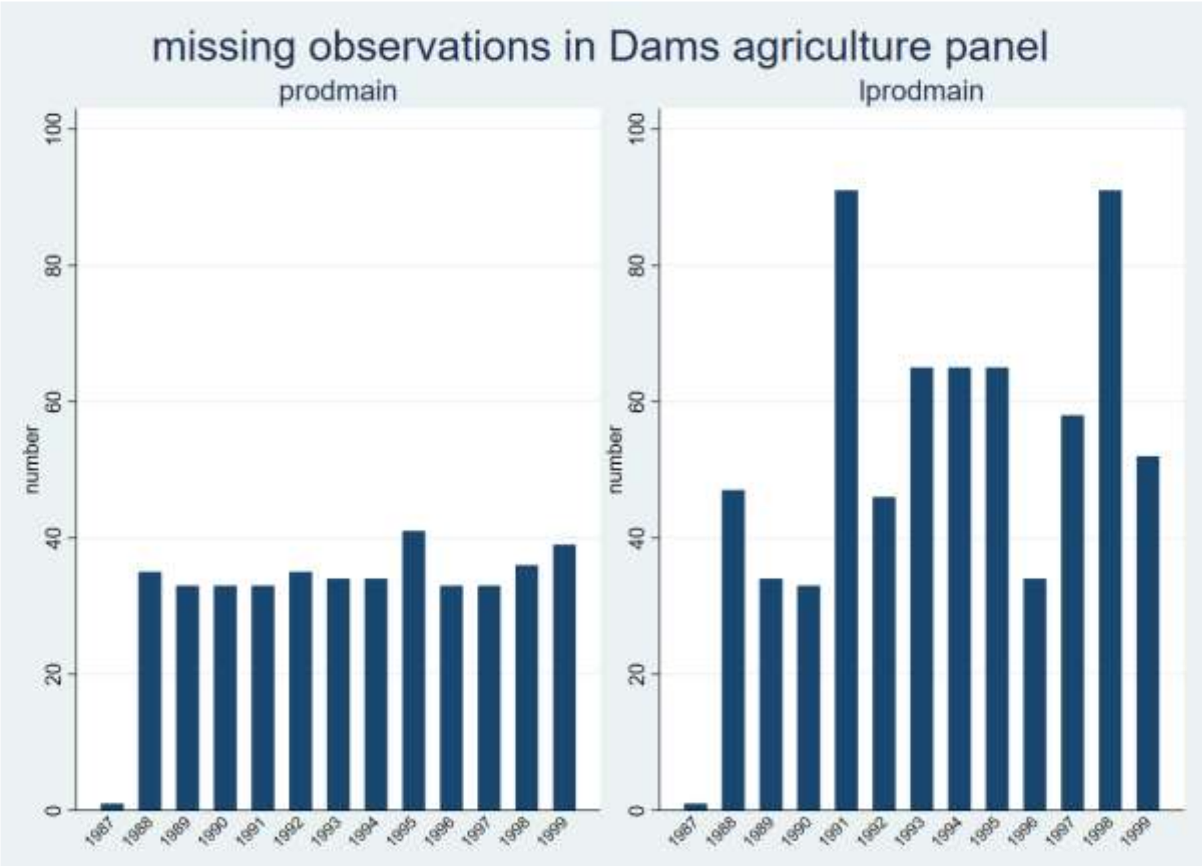
		Area				Inputs	Agricultural production			
		Gross irrigated area		Gross cultivated area		Fertilizer use	Production	Yield	Water-intensive crops	Non-water-intensive crops
		level	log	level	log		All Crops			
		1	2	3	4	5	6	7	8	9
						Part A: FGLS				
Dams	own district	14.528	0.131	114.493	0.094	0.231	0.184	0.152	0.063	0.640
		(13.3)	(0.156)	(47.838)	(0.059)	(0.342)	(0.334)	(0.196)	(0.334)	(0.585)
	Upsteam	17.830	0.198	77.641	0.028	0.256	0.530	0.227	0.569	0.801
		(12.639)	(0.162)	(48.233)	(0.054)	(0.339)	(0.155)	(0.141)	(0.243)	(0.307)
						Part B: Feasible Optimal IV				
Dams	own district	232.092	0.728	325.358	0.875	0.563	0.085	0.033	0.366	0.105
		(235.847)	(1.002)	(263.509)	(0.59)	(1.244)	(0.699)	(0.451)	(-0.782)	(1.349)
B	upsteam ~s	49.754	0.328	58.602	0.088	0.169	0.341	0.193	0.470	0.181
	se	(22.339)	(0.154)	(35.674)	(0.062)	(0.175)	(0.118)	(0.097)	(0.154)	(0.307)
N		4536	4536	4522	4522	4521	7078	7077	7143	6786
First stage *F*-statistic (own district)		8.48	8.48	8.51	8.51	8.50	9.22	9.22	9.03	9.14

Regressions include district fixed effects, state*year interactions, interaction of the number of predicted dams in the state with district gradient, kilometers of river, district area, and district elevation and river gradient*year interactions (see notes to Table II [in ‘Dams’] for a full description of geography variables). They also include interaction of the number of predicted dams in the state with (average) gradient, kilometers of river, area and elevation in upstream districts, river gradient in upstream districts*year interaction, and an indicator for whether the district has any upstream districts. Regression coefficients are multiplied by 100. Standard errors, clustered by district, are reported in parentheses. Production and yield variables are in logs. We use the monetized value of production for six major crops (described in notes to Table I). Yield is defined as crop production per unit of land (Rs. per hectare). Non-water-intensive crops are sorghum (jowar), pearl millet (bajra), and maize, and water-intensive crops are wheat, rice, and sugarcane. The sample includes annual data for 271 districts in 13 states (defined by 1961 census boundaries). Area and fertilizer data cover 1971–1987 and production and yield data 1971–1999. Deviations in sample size are due to missing data. The last row provides the F-statistics from the regression of the number of dams in the district on the predicted number of dams in the own district.

Appendix 1 Table 2: Table correlations among topography category shares

	Panel A: 'correct' topography category shares											
sriver1	1.00											
sriver2	-0.04	1.00										
sriver3	-0.15	-0.50	1.00									
sriver6	-0.12	-0.96	0.30	1.00								
sdistrict1	0.97	-0.03	-0.17	-0.13	1.00							
sdistrict2	0.00	0.96	-0.62	-0.89	0.02	1.00						
sdistrict3	-0.17	-0.19	0.84	0.01	-0.19	-0.38	1.00					
sdistrict6	-0.15	-0.97	0.46	0.97	-0.16	-0.96	0.17	1.00				
elev1	0.21	0.50	-0.40	-0.49	0.23	0.57	-0.44	-0.53	1.00			
elev2	-0.12	0.09	0.22	-0.14	-0.14	0.02	0.35	-0.09	-0.57	1.00		
elev3	-0.12	-0.21	0.39	0.15	-0.14	-0.31	0.48	0.23	-0.62	0.00	1.00	
elev4	-0.09	-0.79	0.03	0.88	-0.09	-0.71	-0.16	0.81	-0.43	-0.20	0.01	1.00
mean topography shares	0.02	0.76	0.07	0.15	0.02	0.69	0.08	0.21	0.54	0.22	0.15	0.09
	Panel B: Dataverse files topography category shares											
sriver1	1.00											
sriver2	-0.60	1.00										
sriver3	-0.88	0.72	1.00									
sriver6	-0.88	0.17	0.59	1.00								
sdistrict1	0.04	-0.21	-0.08	0.07	1.00							
sdistrict2	0.00	0.28	0.06	-0.14	-0.77	1.00						
sdistrict3	-0.04	0.20	0.09	-0.07	-0.91	0.79	1.00					
sdistrict6	-0.05	0.08	0.05	0.02	-0.81	0.29	0.58	1.00				
elev1	0.00	-0.19	-0.01	0.10	0.54	-0.69	-0.48	-0.25	1.00			
elev2	0.02	0.05	-0.02	-0.05	-0.18	0.38	0.21	-0.06	-0.70	1.00		
elev3	-0.02	0.25	0.05	-0.09	-0.47	0.59	0.43	0.22	-0.64	-0.06	1.00	
elev4	0.02	-0.04	-0.03	0.01	-0.48	0.02	0.16	0.80	-0.19	-0.10	0.12	1.00
mean topography shares	0.79	0.08	0.05	0.07	0.79	0.09	0.06	0.06	0.53	0.29	0.17	0.01

Appendix 1 Figure 1: Missing observations in 'Dams' Agriculture Panel by year



Appendix 1 Table 3: Correlation among geology variables

	Sandstone	Basement complex	Deccan Trap	granites	schists	alluvium
Average proportion of district	0.065	0.31	0.11	0.01	0.03	0.45
Sandstone	1					
Basement_complex	-0.20	1				
Deccan_trap	-0.11	-0.22	1			
Granites	-0.02	0.09	-0.06	1		
Schists	-0.05	0.01	-0.04	0.10	1	
Alluvium	-0.21	-0.65	-0.35	-0.17	-0.19	1

Note: 2001 census district.

Appendix 2: Dams, river basins, and districts

In this section, we discuss how dams may have effects in their own and other districts, in districts' neighbours, whether district neighbours may be assigned the 'type' classification used in 'Dams' (upstream, downstream or neither) and what a 'hydraulic' direction of a district might be in relation to a dam.

We also discuss the use of "hydraulic" (Pfaffstetter) units of analysis as in Strobl and Strobl, 2010, and Blanc and Strobl, 2014.

River basins, rivers and districts[93]

In order to discuss how dams may affect districts, an understanding of the intersections of hydraulic flows and administrative areas is required. Most depictions of the effects of dams draw the dam on a river in the headwaters of the river; the dam is filled by rainfall above the dam within the river basin up to its watershed (boundary) with neighbouring river basins. Since water flows downhill and irrigation is generally in flatter lands, often in the river's floodplains, that is where irrigation occurs, generally from canals drawn from or below the crest of the dam. Land in these areas can also be affected by pumped (sometime hydrostatic) groundwater, the regime of which can be affected by the altered flows of the river and seepage or tail flows from the canals. This is the case for the mega dams of the Himalayan foothills in northwest India, where the iconic Bhakra and other dams in the Himalaya feed irrigation systems in the plains of the Punjab, Haryana, Uttar Pradesh, and Rajasthan.

This may be the general case except where major investments divert water into other river basins. But it is also the case that many larger dams are quite far down the river course on its journey to the sea (or border of the country); this is partly because this is where there are suitable dam sites, and partly because large accumulated river flows may be needed to provide ample storage and refill time. In the Damodar river basin (in Eastern India – see Appendix 2 Figure 1), for example, dams are in the headwaters and in the middle reaches, while the areas irrigated are depicted in the lower reaches after the river debouches from the Chota Nagpur (Chhotanagpur) Plateau onto the Gangetic floodplains.

[93] I use the term 'rivers' interchangeably with drainage courses based on hydraulic models derived from DEMs.

Appendix 2 Figure 1: Dams and irrigated areas in the Damodar Valley

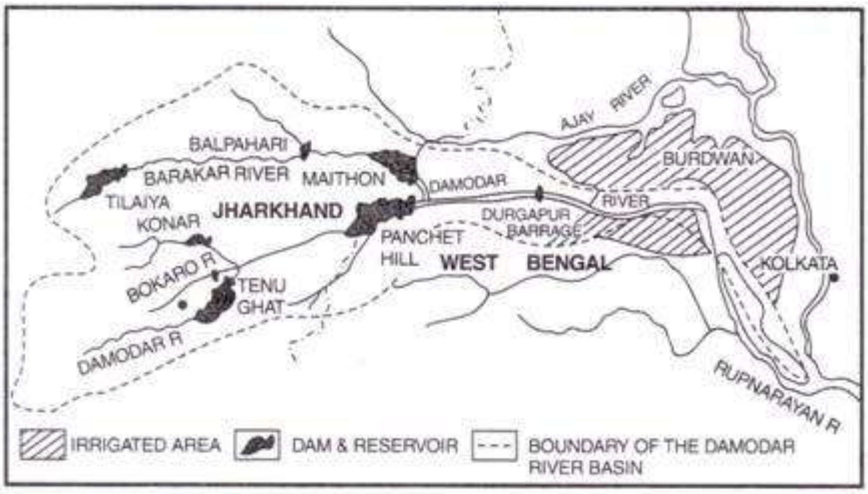
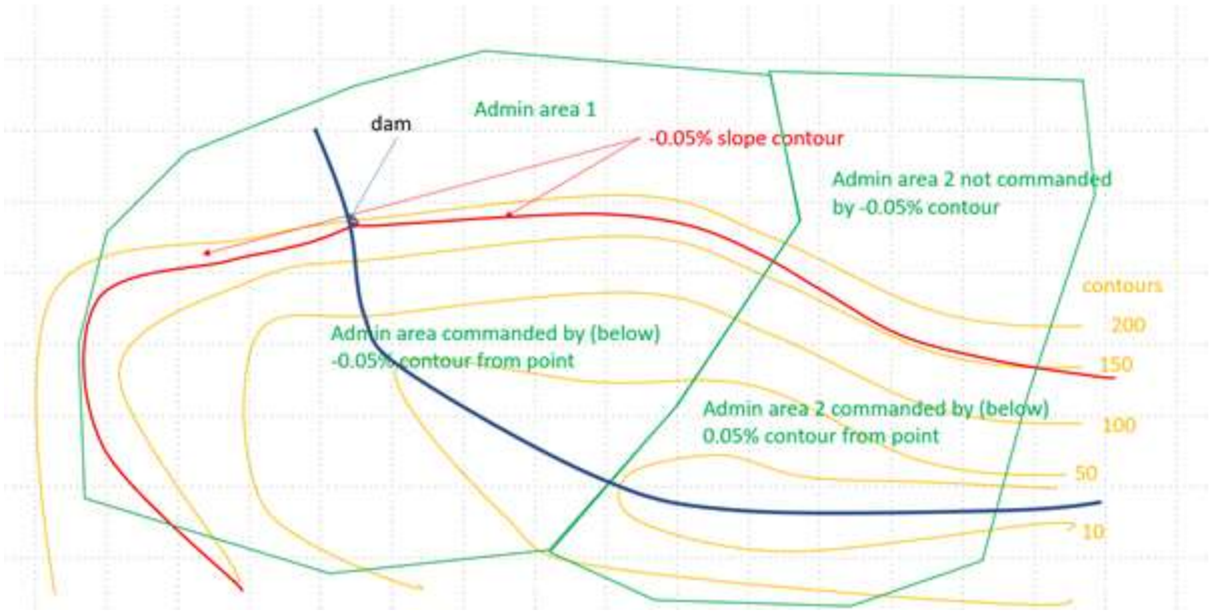


FIG. 18.3. The Damodar Valley Project

The following figure (Appendix 2 Figure 2) illustrates our depiction.

Appendix 2 Figure 2: Schematic of dams, river courses and districts



It is relatively easy to compute the downstream course of drainage from a dam such as illustrated by the blue line in **Appendix 2 Figure 2**; the drainage course coincides with the river course of the river on which the dam is built.[94]

We can find the administrative areas (districts) through, or along the border of, which the river flows. We can find which of these districts is a neighbour to the district of the dam, and

[94] Figure 1 in Blanc and Strobl, 2014 p548, is misleading in that it shows command areas immediately downstream of dams, where in fact they can be far "downstream", and does not show how topography could allow command of irrigable areas in neighbouring "upstream" (higher numbered hydraulic units) as well as downstream hydraulic units. See further below.

we can find the distance from the dam to the nearest point at which it first touches the border of downstream districts, and the length of river course downstream of the dam that runs through, or along the border of such (downstream) districts. I distinguish trajectories through (within) from those along the border of districts, as the effects of the former are probably mainly within the district, while the river course along the border may affect both districts[95]. In the absence of other information, I assume that the effects of border courses are half those of courses which flow through a district. This will be the case where boundary rivers flow through floodplains (the ample plains of the Indus and Ganges for example), but will not be the case where the river flows against a geological structure such that the terrain on one side of the river is very different from that on the other.

This assumes that the effects of dams are mainly confined to areas bordering the river course (within the same river basin[96]). This will be the case where irrigated and groundwater-affected areas are within or bordering the floodplains of the river but will not be true where canals can spread water far from the river course below the dam. This is usually only or at least mainly for mega dams.

An important claim in 'Dams' is that districts with many dams in upstream neighbouring districts fare relatively well in terms of a number of variables. Casual and more careful examination of Duflo and Pande's data, knowledge of India's geographic regions,[97] and the interaction of physiographic and administrative units suggests that the grouping of upstream neighbouring districts is not unproblematic. District boundaries are often aligned with topographical features such as rivers (or estuaries) and watersheds, which means that not only are districts likely to be quite diverse, and possibly contain more than one river basin, but neighbouring districts, 'upstream' or not, are also likely to be quite diverse and themselves comprised of more than one river basin, with different drainage characteristics affecting the relation between dams in these districts and their 'downstream' neighbours.

Further, Duflo and Pande's conceptualisation of the 'causal' variables (number of dams in districts and their upstream neighbours), the variables they introduce to control for the characteristics of 'upstream neighbours', the estimation approach they adopt, and the variables they construct as the empirical realisation of what seems to be their operationalisation of these variables,[98] are so flawed as to make any findings hard, if not impossible, to interpret – interpretation is likely to be entirely unreliable. I find problems with the conceptualisations, their empirical realisation and the econometrics employed in estimation.

'Dams' categorises districts as neighbours or not, and those they assign as neighbours are categorised as upstream, downstream or neither upstream nor downstream (direction).[99]

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95 Because district borders often reflect topographical features, including river courses and geological formations, sometimes the land on either side of a border (or river) is quite different to land on the other; sometimes however they are very similar, as when rivers flow through alluvial (flood) plains. Something is the case for canals.

96 While it is possible to distinguish areas within the river basin within the district and adjust possible district-level effects according to the share of the district within the basin, I have not yet made these computations. I do separate dams in districts in the river basin from those in other river basins, as explained elsewhere. Anticipating discussion below, I have yet to compute geographical characteristics for only those parts of the district which are within the same river basin. Duflo and Pande compute the geographical characteristics of 'upstream districts' on the basins of the whole of all the districts designated as upstream. This can be quite misleading where different river basins within a district have different geographical characteristics. An example is discussed below.

97 See, for example, Chen Han-seng. Agro-Ecological Regions of South Asia, circa 1930. In Thorner, D. (Ed.) Karachi: Oxford University Press, 1996; NBLUSS, 'Agro-ecological Regions of India'. ICAR NBLUSS, 1990. Palmer-Jones, R. (2003). 'Agricultural growth, poverty reduction and agro-ecological zones in India: an ecological fallacy?'. *Food Policy 28*, 423–431. https://doi.org/10.1016/S0306-9192(03)00049-6; https://lotusarise.com/agro-ecological-regions-of-india-upsc/.

98 The theory of measurement states that variables are derived from theories based on concepts realised through operationalisation; they are not given to common sense understanding. 'Dams' does not define what is meant by 'upstream' and, as shown here, it is not at all clear what could have been meant.

99 The data files in the dataverse only contain the variables 'damsum' (dams in district) and 'damsum_upstream' (aggregated 'dams in upstream neighbours') and their 'downstream' and 'neither' complements. The dataverse

The bases of this categorisation of districts as neighbours and the identification of (whole) districts as upstream is not given at any point. While conceptually the neighbour relation is straightforward, and readily implemented either manually (though this could be liable to error), or by GIS software, the basis on which one could designate (whole) districts as 'upstream' is far from clear,[100] and indeed common sense suggests it is problematic because administrative and hydrological boundaries are unlikely to fit any model for making such a designation. Indeed, given a casual acquaintance with maps of districts and the rivers of India, it is immediately obvious that such a conceptualisation (whole or most of districts being upstream of other districts) is entirely implausible. Even with a naïve interpretation of 'upstreamness' such as 'most of (the relevant areas of such) districts are upstream of other districts', 'Dams' makes mistakes. For example, visual inspection of the major rivers of India shows that Nashik has a major river that flows into Jalgaon (i.e. is at least partly hydrologically upstream of Jalgaon[101]), and Jalgoan has no major or even minor rivers evidently upstream of Nashik.[102] The file mentioned above that is not in the dataverse has a variable that shows that 'Dams' identifies that the Girna (a major tributary of the Tapi) flows between Nashik and Jalgaon, and that it flows 'west',[103] but any map of Indian districts shows that Jalgaon is actually (north) east of Nashik. 'Dams' wrongly assigns Jalgaon as upstream of Nashik (and vice versa).

To preview discussion below, this categorisation causes problems: there is no possibility that neighbouring districts can have dams that are both upstream and downstream (both) of district; that district boundaries may coincide with hydrological boundaries so that water flows are common to both districts; that districts are transected by hydrological boundaries (catchment or watershed boundaries) so that dams in one catchment in a district flow to some neighbouring districts but not others, and dams in other catchments (within the district) flow to other districts; and it ignores the presence of canals that can transfer water from one catchment to another.

This section proceeds to discuss issues in identifying neighbours, and the direction (upstream/downstream/neither) categorisation, which I term the characteristic of 'upstreamness'. This is not straightforward, and even within the limitations of this schema, as noted, 'Dams' makes clear mistakes in the direction of those it designates as neighbours, and also its designation of neighbours has errors. There are (and were at the time the authors were working on 'Dams') straightforward GIS tools to identify district (polygon) neighbours. 'Dams' could have been limited by the lack of precise location of dams, but knowing both the nearest city and the river on which the dams were located should have

files do not specify which districts are neighbours, or which are upstream. I reverse engineered their assignment of neighbouring districts by finding which combinations of neighbouring districts gave the values of variables such as 'sum of areas of upstream neighbours'. My reverse engineered reproduction of Duflo and Pande's assignment of neighbours and direction for the most part coincided with those in a file not in the dataverse subsequently made available by the authors. Details of this can be obtained from the author. The reverse engineered assignments depend only on Duflo and Pande's variables and not on whether the districts so assigned are in fact (GIS) neighbours (or upstream).

[100] The 'upstream' relation is symmetric, so that district A that is upstream of district B, entails that district B is downstream of district A. Neighbours that are not in an upstream/downstream relation are by implication neither upstream not downstream. 'Dams' does not allow a 'both upstream and downstream' category.

[101] See below for why a hydrological interpretation of Duflo and Pande's categorisation seems appropriate, and what might be meant by hydrological direction between administrative units.

[102] Our GIS, explained below, shows one large dam in Jalgaon which appears to be upstream of a (very small) part of Nashik.

[103] There are two variables giving direction in Duflo and Pande's file; the variable 'direction' shows 'west', while the variable 'newdir' (new direction) shows 'east'. These variables do not have variable labels, and no explanation is given. The entries for Jalgoan show Nashik as "east" for both ; 'direction' and ; 'newdir'.

allowed quite accurate assessment of where dams were located on rivers, and hence which dams were hydraulically[104] upstream of neighbouring districts (see below).[105]

Neighbours

'Dams' used a Global Administrative areas (GADM) shape file of Indian Districts (or a similar one) corresponding, I infer, to the set of districts in the 1991 Indian Census; however, it appears that some neighbours are not correctly identified (omissions). An example of a missing neighbour is Aligarh in relation to Agra. Aligarh shares a length of border with Agra (in version 3.6 of GADM[106]) but is not designated as a neighbour in the 'Dams' file 'distlist_full_md.dta'.[107]

Districts which are neighbours in any GIS (polygon) map of Indian districts can be easily assigned using either the 'PolygonNeighbour' or 'PolygonToLine_management' processes in ESRI GIS or similar software. Similar procedures were available in the early 2000s and in other software. In both cases any district (polygon) that has at least one common boundary point will be designated as a neighbour, and the length of common boundary computed.

Obviously, neighbours may have a lengthy or short common boundary, or a single point (corner) common boundary;[108] these are 'Rook' and 'Bishop' neighbours, respectively ('Queen' neighbours have both Rook and Bishop neighbours). Anticipating discussion of direction below, we note that hydraulic relations between neighbouring districts are not necessarily related to the nature or length of border between them. For example, Bishop neighbours can have meaningful upstream/downstream relations, as between Mysore, Salem, Dharmapuri and Periyar, which meet (effectively) at a single point; Salem is clearly downstream of all of Mysore, that part of Dharmapuri that is in the Cauvery basin, and that part of Periyar that is in the Cauvery basin and upstream of this junction. However, the topography makes it unlikely that Salem is downstream of much of Periyar at this corner point (ie downstream in terms of the Cauvery and Palar rivers, which join where these districts meet). Other parts of Salem are downstream of Periyar in terms of the Bhavaniriver (and other rivers with dams in Periyar), a tributary of the Cauvery which joins the Cauvery lower in Salem District than the junction between the Cauvery and the Palar. Lengthy common boundaries may (river flowing along the common boundary) or may not (common

[104] I infer that 'Dams' employed a hydraulic definition of 'upstreamness'. Simply put, this means that the river on which the dam is located, or which is nearest to the 'nearest city', flows into the neighbouring downstream district. See further below.

[105] For many dams the 'river' variable in the ICOLD database may not have been very informative. Nevertheless, the DCW rivers, GIS delineation of river courses, and the 'nearest city' would have allowed almost all dams in ICOLD to be located within the river basin in which they actually are, and indeed where on the river using a "nearest point on polyline" function. River basin GIS are readily produced from DEMs, to which 'Dams' had access and which were the bases of their district elevation and slope and river slope variables (in their dataverse files).

[106] GADM version 3.6 is the version I use. 'Dams' (or their research assistants/contractors) may have used another version. The India Census Administrative Atlas (Census of India, 2004), also clearly shows which districts have common boundaries in each census.

[107] 'Dams' does not seem to have included metropolitan areas of Mumbai and Bangalore but has included Azad, Kashmir and Gilgit, which are beyond the line of control between Indian and Pakistani administrations.

[108] 'Node' neighbours include corner neighbours and boundary-crossing neighbours where the crossings are single points. Since this point could be where a river passes from one district to another, point/node/Bishop/Queen neighbours should probably count as neighbours for our purposes. An example is the relationship between Mysore and Salem (1991) districts, where the boundaries of four districts which have (Mysore, Dharmapuri, Periyar and Salem) meet, where the Cauvery emerges from the border between Mysore and Dharmapuri into Salem at the head of the Mettur Dam reservoir (Periyar district, which shares a corner boundary at this point shares a border with Mysore along which a tributary of the Cauvery (the Palar river) flows into the Cauvery so that it is upstream of a very small portion of Dharmapuri but commands most of Salem). Similar points occur at the boundaries of Rae Bareli, Fatehpur, Allahabad and Pratabgarh; Bishnupur, Thoubal, Churchandpur and Chandel; East Siang, Dibhang Valley, Tinsukia and Dhemaji.

boundary along a watershed) entail the possibility of hydraulic relations between neighbouring districts.

Direction

'Dams' does not report how the categorisation of direction between neighbouring districts was made, and the method (set of rules for assigning direction) cannot be inferred from the data because it is clear from the obvious mis-assignments, such as between Nashi and Jalgaon, that reverse engineering would be impossible.[109] I argue below that no meaningful direction assignment between districts can, or should, be made based on spatial contiguity (being neighbours) or proximity, without reference to both topography and (surface and especially groundwater) hydrology or to the existence of canals or other artificial means of transferring water over space.

At no point does 'Dams' describe its concept of 'upstream'; the dictionary definition of the term relates mainly to points on a stream, but sometimes it is used to denote position in sequences of processes, where upstream processes are inputs into downstream processes, or prior in time when upstream events take place before downstream ones.[110] It does not pertain to topographical or indeed hydrological relationships between administrative areas.

My intuition is that the meaning in 'Dams' is 'hydrologically' upstream,[111] which I interpret in terms of hydrological flow models of probably unmodified (by humans, dams, canals, tunnels, roads, railways or other human-made infrastructure) terrain, usually derived from DEMs. I term this hydrological 'upstreamness', and it has some virtues.[112] Empirically 'Dams' applies its definition of upstreamness to neighbouring districts and chains this relation for districts which are 'upstream of upstream neighbours'. But it is plain that not all districts which are 'upstream' of district A will be upstream of district B that is downstream of district A[113]. This is because it is possible that (any part of) district C, which is (all or partly) upstream of a part of district A may not be upstream of (any part of) district C.

Hydraulically, the relation is not recursive beyond the first neighbour. For example, part of Nashik in the Godavari river basin is (hydraulically) upstream of (part of) Ahmadnagar district, a part of which in the Krishna basin is (hydraulically) upstream of Pune district, nearly all of which is in the Krishna basin but none of which is in the Godavari basin. Hence, it would be wrong to classify Nashik as 'upstream' of Pune, as Dufle and Pande do.

Similar issues arise wherever districts are transected by watersheds (the boundaries of river basins); the watershed between the Godavari and the Tapi and Narmada rivers along the Satpura range means that such districts (transected by the watershed between the Godavari and Narmada or Tapi), which are partly upstream of districts fully within these river basins, are only partly (or not at all) upstream of districts further downstream within these basins. This (non-)relation occurs also between districts in sub-basins (of tributaries) of larger basins. Thus Vidisha in the Ganges Basin (on the Betul river) is (partly) upstream of Guna,

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[109] While we infer that a manual assignment was used by the authors of 'Dams', which could be associated with errors, code that implemented their assignment might also have had mistakes in the algorithm used. Manual assignment might, for example, see a neighbour where in fact there is no common boundary. Computer code might contain errors or surprising limitations.

[110] Rare or newer meanings are 'troublesome' and 'prior in transcription'.

[111] "Land in the catchment area upstream to the reservoir" (p 608); the "'upstream' coefficient captures the impact of dams built in neighboring *upstream* districts (and we often refer to this as the downstream effect of dams)" (p 623).

[112] Strobel and Strobel, use a related type of upstreamness in their empirical model based on Pfaffstetter units rather than administrative units (districts). Their concept is also deeply flawed when assessing the potential impacts of dams, since Pfaffstetter units are essentially basins and sub-basins of rivers, which do not entail that a dam in an 'upstream' (Pfaffstetter) unit can command much if any of a 'downstream' Pfaffstetter unit in the same river basin.

[113] Duflo and Pande have 'upstream of upstream' variables, where any district that is 'upstream ' of A is 'upstream of upstream' of B which is 'downstream ' of A (to which A is 'upstream').

which itself is (partly) upstream of Kota (in the Chambal sub-basin), and of Shivpuri (in the Betul sub-basin), but no dam in Vidisha is upstream of Kota.

Thus, it is not clear how districts can meaningfully be categorised as 'upstream', 'downstream' or 'neither'. This application (to the hydrological, let alone irrigational, direction of neighbouring districts[114]) of the concept of 'upstream' makes no sense in hydrological terms.

Hydraulic direction

Hydraulic directions can be computed from DEMs as used in the computation of district elevation and district and river slopes (the same or similar DEMs to that used in 'Dams' – there is no need for them to be the same, although presumably it is convenient; one might want to use a higher resolution DEM for drainage calculation, and the size of pixel in the DEM may well influence the topography variables computed; this maybe particularly relevant to river slope calculations because larger pixel sizes will encompass more of a district than the actual river course). The process involves applying GIS procedures to the DEM to extract drainage (river) courses. These traces (lines) are the 'predicted' flow of water within the area, rather than a direct digitisation of the river course. These procedures delineate river basins and sub-basins (tributaries) which can be superimposed on districts to extract the districts through and along the border of which water from dams would flow by gravity. The intersection of the drainage paths at the point (latitude and longitude) of dams and with district boundaries forms the basis of my definition of directional relations between districts. The distance to the nearest point of a district (on its boundary), and the length of the drainage course within and along the border of districts,[115] are also calculated as 'distance_to_district', 'distance_within_district', and 'distance_along_borderOf (own or other)_district' . A district is upstream if any dam in the NRLD/WRIS dam database has a drainage course with a segment within, touching, or along the border of the district; it is an upstream neighbour if it is a neighbour and there is a segment from any dam that is (hydrologically) upstream of the district to which it is a neighbour,[116] whether or not the neighbours have dams themselves.

Note that, only if there is a dam in the database upstream, are drainage courses calculated and upstreamness computed. There may be rivers which are not yet dammed that could in the future be dammed; some potential upstream relations may therefore not be identified. An alternative procedure would be to use a more complete definition of rivers (as in as_riv_15s) with accumulated catchment area (or rain-adjusted catchment area) above a certain size to define the river courses which provide the hydraulic link between districts and to define the set of 'upstream neighbouring' districts, at least for the purpose of calculating the geographical characteristics of neighbouring districts of a particular orientation (direction). However, this would be computationally demanding, and complicated by the need to adjust for rainfall in each catchment in controlling for its geographic properties. Thus, a district with a large catchment with low rainfall is less likely to have dams than one with more rainfall (given other parameters of relevance in hydrological flow models). As discussed in relation to the siting of dams, account might also need to be taken of other underlying geological and other variables which determine whether there are suitable and feasible dam sites. The computation of river streams from more than 5,000 dams and the assignment of sequence to segments in the drainage course is already demanding (> 6 hours).[117] It would be much

[114] It should be noted that the hydrological effects of dams mainly occur in three ways; by altering river flows, by enabling and feeding canals and by effects on groundwater through these two processes.
[115] I compute a drainage course as along the border if it is within 1km of the border.
[116] It may or may not be the case that this 'upstream' neighbour has such a dam itself; it may have a dam further upstream in another district the drainage of which flows through or along the border of both districts.
[117] An important procedure used in the computation does not always return river segments in proper order (so that segments are properly defined as upstream when they are), entailing quite complicated additional

more so if all possible upstream rivers were to be considered, and there would be considerable arbitrariness in determining the proper minimum size of river for which to compute its river course.

Contiguity (being a neighbour) and direction

Contiguity (having a common boundary) may or may not entail an exhaustive (all possible) and exclusive (only) upstream/downstream/neither relationship between neighbouring administrative areas; district neighbours may be both upstream and downstream in the sense that dams in a neighbour may have (river and canal flows, and groundwater) effects in areas in the district (of interest), and vice versa. Indeed, using a hydraulic definition of direction, more than half of India's 1991 districts have at least one neighbour with which they have a 'both' (upstream and downstream) relationship, often with several neighbours. Indeed, quite a number of districts that have a hydraulically 'upstream of upstream' relation with district A are also 'downstream of downstream' of district A (ie a stream from district B passes through at least one neighbour to A and a stream from A passes through at least one neighbour of B to A. This arises because rivers with dams on them (see below) cross and or run along the border of both neighbours as well as intersecting them.[118] For example, using a 'hydraulic' definition of direction, Adilabad has a 'both' relationship with five of its six neighbours, since several rivers define the boundaries between them.

Further problems with the 'Dams' data files are that the assignment of direction is sometimes wrong.

Districts and their neighbours in 'Dams'

In order to assess the 'neighbour type' variables in 'Dams' we compare hydraulic neighbours with the variables for neighbours and their 'direction' contained in the file 'distlist_full_md.dta', which is not in the dataverse but was made available to use in December 2020. Before that we reverse engineered Duflo and Pande's neighbours using the values of the variable, 'km2' and 'km2_upstream. The definitions of these variables suggest that the sum of 'km2' of the districts designated as upstream neighbours should sum to km2_upstream for each district. This is indeed so in the majority of cases; the 'distlist_full_md.dta' file confirmed this supposition.[119]

In a number of cases neighbours in 'Dams' are not in fact neighbours. There is a cluster of districts whose neighbours are simply wrong. Darbhanga and Khagaria, Etah and Mathura; Dhemaji and Jorhat; Giridih and Sundargarh, Gumla and Pashchim_Singhbhum; West Garo Hills and West Khasi Hills are not neighbours. In a number of other cases where districts are not neighbours this is because an estuary (Kheda and Bharuch) or the Rann of Kachchh (Barmer, Jalor and Kachchh) separates the districts 'Dams' assign as neighbours.[120] There is no common land boundary between these districts.

Also concerning is the fact that 'Dams' uses the wrong hydraulic direction between districts. Because we use a specific definition of hydraulic direction determined by the computed river

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procedures to compute the proper order of segments. Where river courses cross international boundaries, further problems arise if the river course has been "clipped" at the international boundary. .

[118] In most cases the 'both' relation is a result of lengthy common borders aligned with a river with tributaries on both sides.

[119] We get the same neighbours using sum of 'riverkm' of upstream neighbours equal to riverkm_upstream. The other variables which exist in district and _upstream versions (number of dams, district elevation and slope categories, and river slope categories) cannot readily be used for reverse engineering the neighbour type because values of zero multiply the combinations of neighbours whose values sum to the upstream variable. There are additional problems that, with the geographical variables, the upstream variables are area-weighted sums (although this is not stated in 'Dams') and accuracy may be limited by the number of decimal points.

[120] DP seem to have included Gilgit and Azad Kashmir in their map of India, but these districts are not on our map, or in any of the outcome datasets, and so do not appear as neighbours in our data.

course, our specification of the 'correct' direction will not be the same as in in 'Dams' if the paper did not use the hydraulic definition (but never defined its categorisation), or mistakenly used the hydraulic definition. Since there is not coherent way to assign districts as up- and down-stream it is not really meaningful to compare the assignments in 'Dams' to those we find using our definition of hydraulic up/downstream relation. Nevertheless, we find (Appendix 2 Table 4) that where 'Dams' categorises the direction as 'U' but that the relationship of both 'U' and 'D' is 'down' in 195 district neighbour pairs (1981 districts).

Appendix 2 Table 4: Districts mis-allocated to neighbour type category (1981 districts)

'Dams' Neighbour_type	Missing from category	Wrongly in category	Neighbour is both upstream & downstream	total number of districts
upstream	252	103	195	424
downstream	212	94		424
neither	193	208		424

Results are sensitive to the specification that ANY dam upstream creates an upstream of both relation; in some cases only 1 dam is ACTUALLY upstream

We compute a district as neighbour when even just one dam is upstream. Because we have many neighbours which are both up- and downstream, the comparisons we can make are between our 'upstream' and 'both' and Duflo and Pande's 'up', and between our 'downstream' and 'both' and their downstream allocations. We can also compare our neighbours with theirs.

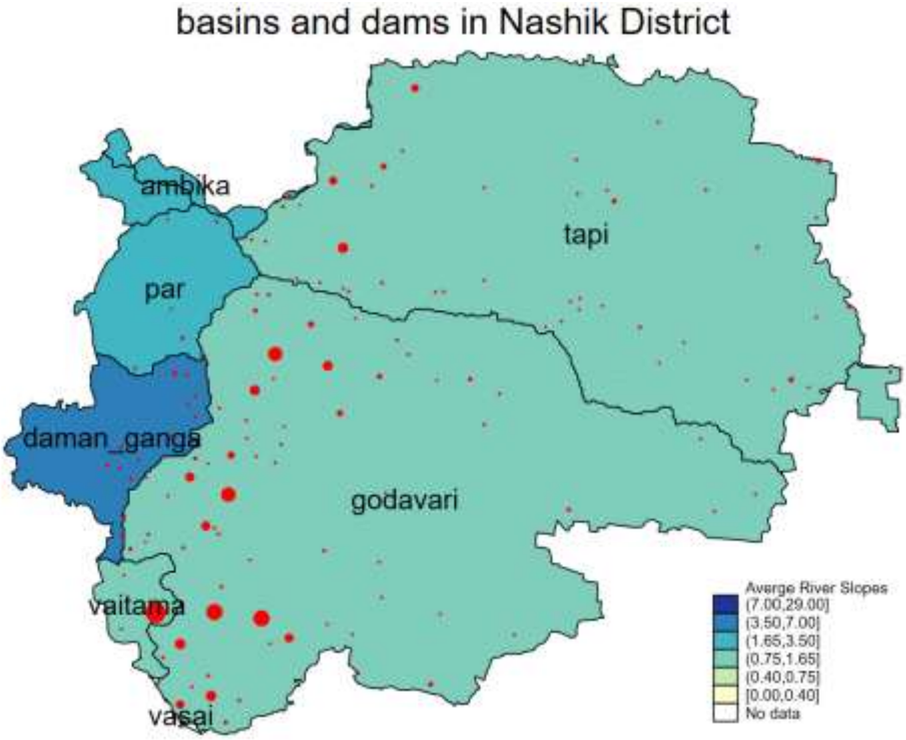
Eighty-five pairs of neighbours do not appear as neighbours in Duflo and Pande's data. Some of these neighbours are Bishop neighbours, and some are with the Rann of Kachchh which is not a district. Nevertheless, many of the missing neighbour pairs have upstream and, or downstream dams.

But in some cases, 'Dams' clearly gets the direction wrong; this is the case for the Jalgaon/Nashik (or the Dhar/Indore pair). The paper classifies Nashik as downstream of Jalgaon, but as **Appendix 2 Figure 3** shows, in fact Jalgoan is downstream of Nashik, except for one dam. Furthermore, although some 40% of the dams in Nashik disgorge into Jalgaon, others disgorge into Dhule, Aurangabad, Ahmadabad, Thane and Valsad.

Appendix 2 Figure 3: Directions of flow from Nashik District

This has obvious implications not only for the calculation of the number of upstream dams in upstream neighbours, but also for the calculation of the geographies of upstream neighbours as described in ‘Dams’. The different river basins in Nashik, which disgorge into different neighbouring districts have different geographies**; Appendix 2 Figure 4** shows that, for example, the average river slopes differ between the basins within Nashik (of course, the proportions of different river and district slopes and elevation categories also differ). This is not an isolated case, as shown in the main text (see **Figure 2** there).

Appendix 2 Figure 4: Average river slopes in different river basins in Nashik district



Pfaffstetter units

Strobl and Strobl, (2011) and Blanc and Strobl, (2014), suggest that hydraulic units defined by the Pfaffstetter numbering system provide more appropriate units within which to assess the impacts of dams. They provide a visual comparison of the overlay of administrative and hydraulic units for Africa, and a detail on Southern Africa to support their preference for using hydraulic units. They also provide a similar overlay for South India.

However, similar problems occur with Pfaffstetter areas as units of both direction and impact (as used by Strobl and Strobl and Blanc and Strobl). As shown below, it is clear that a dam in an 'upstream' (higher numbered) Pfaffstetter unit may or may not command (have hydraulic or even canal effects) in much if any of downstream (lower numbered) Pfaffstetter units (neighbours or not),[121] but can have effects in higher numbered Pfaffstetter units which may well be commanded by canals from the dam.

In the Pfaffstetter system river basins are comprised of a hierarchy of sub-units within an overall watershed, divided up by tributaries that flow into the main stem of a river that drains the entire watershed[122]. The Pfaffstetter system allocates increasing digits sequentially to sub-basins (tributaries) and inter-tributary regions upwards from the termination of the main stem at an ocean. Tributary *sub-basins* are the basins of tributaries, and areas between the

[121] Pfaffstetter areas are organised hierarchically from the mouth of the river. There are two types of unit – tributaries or (sub-)basins (even numbered) and inter-(sub-)basin areas (odd numbered). It is easy to understand that neighbouring sub-basins will have headwaters very similar in altitude to their neighbours. A dam in the headwaters of neighbouring sub-basins may command large proportions of each other, but a dam near the main river course in a 'higher' sub-basin or inter-basin unit will command little if any of the neighbouring lower units of either type.

[122] Strobl and Strobl, and Blanc and Strobl use the term "basin" to refer to both the overall river basin and to sub-basins within this over all basin; that is they use this term for tributaries and for inter-tributary reaches of the main river, as well.

junctions of tributaries with the main stem of the river are *inter-basin* regions. Each inter-basin is allocated an odd number starting with 1 at the lowest point of the main stem (which drains the largest area), and the sub-basin of each tributary is allocated an increasing even number.[123] Sub-basins can be further sub-divided into inter- and sub-basin areas, adding further odd and even digits to the Pfaffstetter code in the same way.

The Pfaffstetter numbering system can be illustrated using the Cauvery basin in south India (**Appendix 2 Figure 5**); the Cauvery is differentiated from the west flowing rivers of the Deccan Plateau region, and the east flowing rivers that border the Cauvery (eg to the north, the Krishna) at Pfaffstetter level 4 coding (4638),[124] and the Cauvery basin is further subdivided at levels 6, 7[125], 8, etc[126]). Level 4 codes have 4 digits, level 6 have 6 digits, and so on.

Appendix 2 Figure 5: Cauvery river basin and Pfaffstetter units

Note: Red = Cauvery basin – level 40; black = level 6; green = level 7.

All dams in a higher even-numbered unit in the same basin disgorge into the immediate lower level odd-numbered unit but may not disgorge into an immediately lower or neighbouring even-numbered unit, or into even-numbered units downstream of the next odd-numbered unit. Dams in an odd-numbered unit will not disgorge into a lower even-numbered Pfaffstetter unit (453809 does not disgorge into 453808, nor 453808 into 453806). Lower (and higher) numbered level 6 units which are neighbours to 4538xx, such as 4536xx, 4537xx, 4539xx and 4540xx are in neighbouring basins (the Krishna, Pennar, Ponnaiyar and west flowing basins, respectively) so these neighbouring basins can only be hydraulically affected when inter-basin transfers are enabled by pumping and/or canals or tunnels.[127]

[123] Areas which do not drain (closed regions) have code 0 (zero).
[124] Along with some other major river basins (Ganges, Krishna, Mahanadi, Godavari). The Indus and Brahmaputra/Ganges are differentiated at level 2.
[125] Not all level 6 sub-basins are divided at level 7, and so on.
[126] Level 5 coincides with level 4 in this case.
[127] There can, of course, be economic spill-overs into neighbouring basins.
It is worth noting that waters impounded behind the first proper colonial dam on the Periyar river in Kerala, which flows westwards to the Indian Ocean and was constructed around 1894, were transferred eastwards in the Vaigai

Disgorging into is not commanding

However, disgorging into or through a unit of land area is not the same as commanding areas within it; the areas of land potentially commanded from a dam in a Pfaffstetter unit, as with districts, is determined by the potential for gravity irrigation (in the absence of pumping or inter-basin tunnels). This is evident from casual inspection of the elevation of the land or contours.

Thus, adding the elevations (or contours) we see that the biggest dams in the Cauvery basin (the Krishna Rajah Sagara (KRS) and Mettur) are in both cases in the lower elevations of their Pfaffstetter units (453809 and 453805). KRS can potentially (from an elevation point of view) command little of its own unit (453809) but can command some areas lower in units 453806, 7 and 8, as well as the lower areas on 453805 and 4 and below, should there be appropriate canal or in-river and barrage conveyance structures. The famous Mettur dam completed in the 1930s (in the lower area on 453805) can command little of its own unit, but in terms of elevation can potentially command the lower areas of 450804, 03 and 02 and most of 453801. The Bhavanisagar dam, completed in 1955 in the lower reaches of 453804, (and several other smaller dams in the headwaters along the eastern sloping watershed of the Western Ghats) also commands (from an elevation perspective) the lower reaches of 453805 (a higher numbered Pfaffstetter unit) as well as lower areas in 453803, 02 and 01.

In reality, however, as **Appendix 2 Figures 6** and **7** show, areas nominally irrigated below these latter two dams (Bhavanisagar and Mettur) are considerably more limited.[128]

basin, which flows to the Bay of Bengal, and have been used to irrigate areas in Madurai district. (See Mahabaleshwar. and Nagabhushanm, for a discussion of existing and potential inter-basin transfer schemes in India.) In Peninsular India the Parambikulam–Aliyar project (1962–68) involves dams which enable the transfer of waters from west flowing rivers of the Periyar basin from districts in Kerala to the east into districts encompassing parts of the Godavari basin of Tamil Nadu (and from Pfaffstetter units in the Periyar to Pfaffstetter units in the Godavari basin); they are consequently not classified as upstream by the Strobl and Strobl approach. Major inter-basin transfers also occur in the Indo-Gangetic basin, primarily from the Indus to the Ganges. The Kurnool-Cuddapah, dating back to the 1860s and rehabilitated in the 1980s, transfers water from the Krishna basin to the Penna from a Pfaffstetter unit that would not be classed as upstream by Stobl and Strobl. Duflo and Pande correctly classify Cuddapah as neither up nor down, as does our own approach without canals (see file district_full_md.dta).

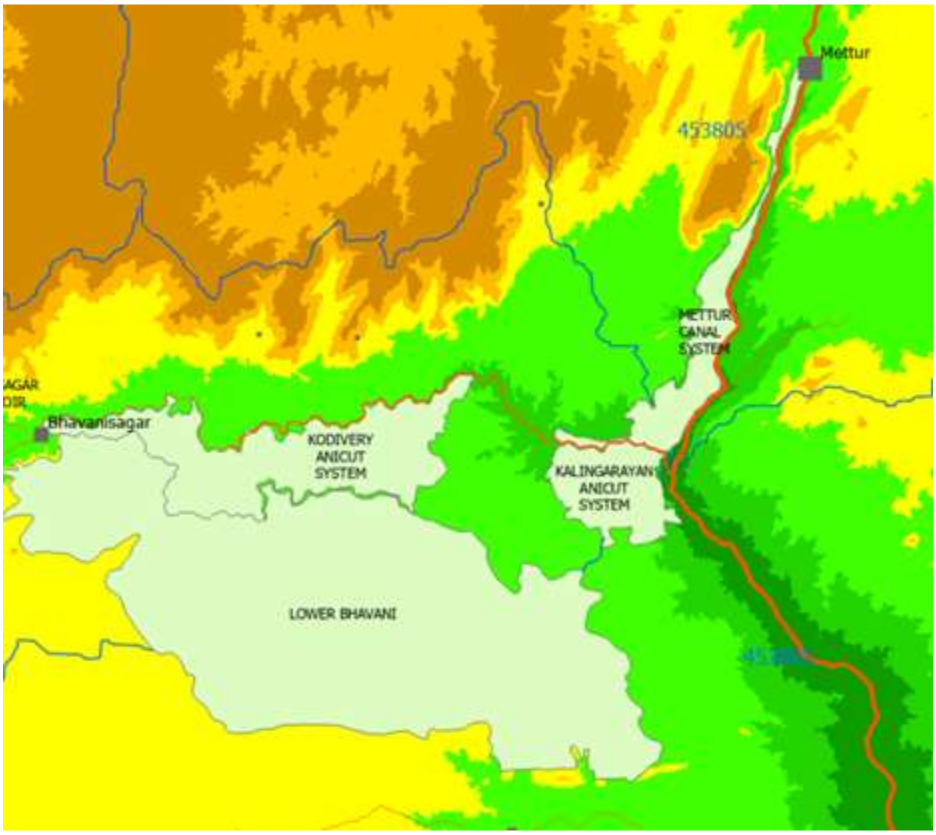
[128] Another potential example is the Rihand dam in UP. This dam, one of, if not the, largest (irrigation) dams in India, was constructed between 1952 and 1962, and discharges into the Rihand river, which shortly joins the Sone, from which irrigation canals run left and right from the Indrapuri barrage (constructed, at the same site as the original Sone anicut built in 1873–74, in the mid-1960s and commissioned in 1968), some 169 kilometres downstream of the Rihand's impoundment point. The left and right bank canals feed the districts of Varanasi, Ghazipur, and Bhallia in Uttar Pradesh on the left bank, and Rohtas, Bhojpur, Gaya, Aurangabad (Bih), and Patna in Bihar on the right bank (via the former Son canal), and Pfaffstetter level 6 units 45242 and 45243, respectively.]

Appendix 2 Figure 6: Areas shown to be irrigated below the Mettur and Bhavanisagar dams

Source: Screen capture, WRIS 'old_map', January 2020.

The actual command areas illustrated – which exceed the areas actually receiving water from either dam, although their groundwater resource may be affected by these dams – are considerably smaller (see **Appendix 2 Figure 7**).

Appendix 2 Figure 7: Areas in irrigation command areas below the Mettur and Bhavanisagar dams



Overlaying the Pfaffstetter units on the purportedly irrigated areas below the Mettur and Bhavanisagar dams shows quite clearly the problem that not all, or even a majority, of the neighbouring odd-numbered downstream units could be or have been irrigated from these dams.

It is also clear that a dam high enough in a lower numbered Pfaffstetter unit can command (by gravity) areas in higher numbered Pfaffstetter units in the same basin, or even Pfaffstetter units in neighbouring basins, by construction of canals or tunnels. Thus the Bhavanisagar dam in Pfaffstetter unit 453804 is at about 270 meters above sea level, while much of Pfaffstetter unit 453805, a higher number unit, is at an elevation below 230 meters at a distance of about 60km; that would entail a slope of more than the 0.05%, which is required for water to flow in a canal. This configuration of dam crest elevation and topography would allow considerable areas of 453805 to be irrigated from the Bhavanisagar dam even though it is in a lower numbered hydraulic unit.

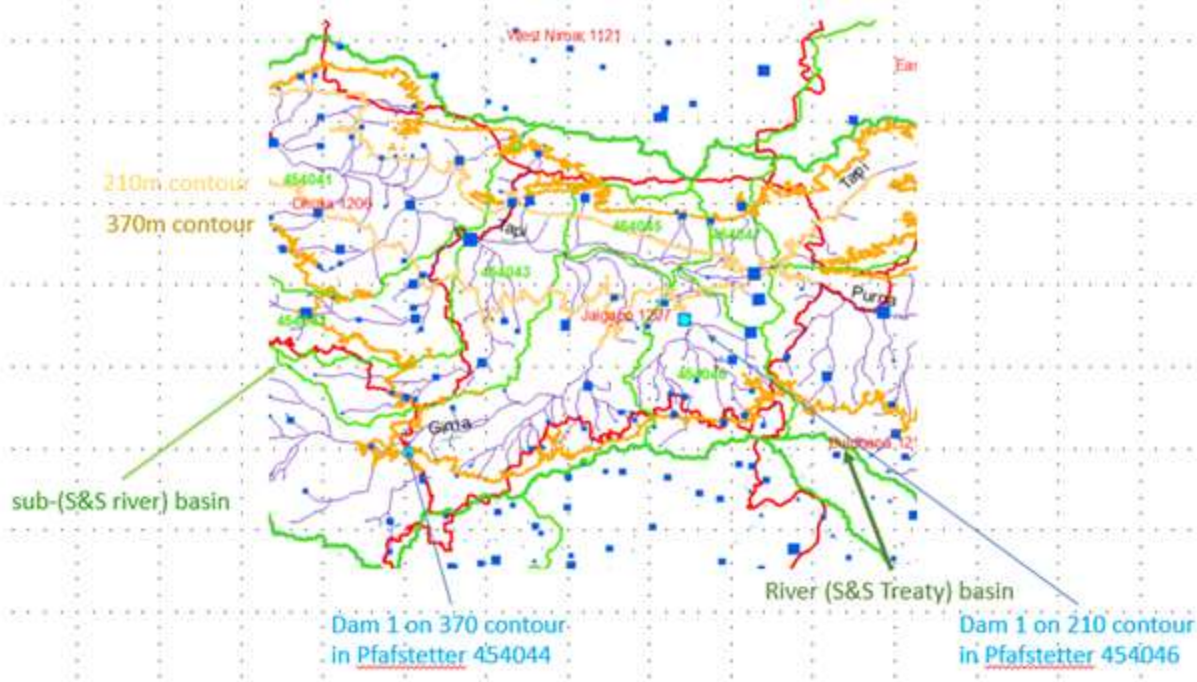
Districts and Pfaffstetter units in the Cauvery basin

Districts perform little better as units within which to analyse the effects of dams. While Mandya, Mysore, Erode, Kapur and Chamarajanagar districts are almost entirely within the Cauvery Basin, there is more than one Pfaffstetter unit within each district, many of which do not disgorge into the same neighbouring district, and dams within any district may not command significant portions of their own district or indeed neighbouring districts that are at least partly downstream. Dams in the other 26 (2001) districts which are at least partly in the Cauvery basin are even less likely to command the majority of the area within their own district, let alone districts that may be at least partly downstream of part of the dams' own district.[129] The largest dams, the Mettur and Bhavanisagar, though not relatively 'high' in their respective districts, either command areas in a largely neighbouring district, or in only part of their own district and, in the case of Bhavanisagar, not at all in any neighbouring district.[130]

Districts and Pfaffstetter units in part of the Tapi basin

The Tapi basin in western India provides another real-world example of hydraulic units. Level 6 Pfaffstetter units are designated 45404x (the neighbouring basin to the north is the Narmada, designated 45405x). Unit 454041 is the lowest inter-basin, and 454042 is the first tributary sub-basin of the Tapi. The next upstream inter-basin is 454043 and is downstream to its neighbours 454044 (a tributary sub-basin) and 454045 (the next upstream inter-basin on the main stem); 454041 is clearly downstream and neighbour to both 454042 and 454043. The latter is downstream to its neighbours 454044 and 454045. Pfaffstetter unit 454044 is downstream and neighbour to 454046, but it is not clear if it is downstream to its neighbour 454045. However, the Pfaffstetter numbering system makes unit 454045 upstream of 454044, in the sense of being a higher number, but not vice versa – yet they both originate from the same river junction.[131]

Appendix 2 Figure 8: Dam potential commanded areas and hydraulic units – Tapi basin



A dam on the 370m contour in the lower left quadrant of Appendix 2 Figure 8 is in Pfaffstetter level 6 unit 454044 and potentially commands about 50% of that unit (green polygons) and most of its downstream neighbour 454043 (provided a canal on the left bank

[129] Since there were fewer districts in earlier periods, these problems of incongruity between district and hydraulic areas are greater.
[130] Among the neighbours to Salem the authors of 'Dams', seemingly using 1991 districts, list Dharmapuri and Periyar as upstream and Tiruchirappalli as downstream, with South Arcot as neither. Periyar is both upstream and downstream of Salem. At least one dam is on the border of Tiruchiruppalli and Salem.
[131] Strobl and Strobl do not make their algorithm for allocating neighbouring units as upstream clear; in personal communication Eric Strobl suggested they used dams in the immediate upstream neighbour (one higher digit) to denominate dams upstream.

diverted water into that neighbour),[132] but could not command areas of its own unit (454044) above the 370m contour. The (rather larger) dam on the 210-meter contour in 454046 (right centre of the figure) would command little of its own unit, or of its downstream neighbour 454044, but it could command much of the higher-numbered unit 4464047.

Finding the areas that could potentially be commanded from a dam is evidently a complex problem which must take into account not only the elevation at which water is potentially available, but many features of the terrain that would determine the feasibility and cost of conveying water to potentially irrigable land. Not all land is worth irrigating, or can be irrigated at reasonable cost; dams will be located not only by the feasibility of the site (strong impermeable rock formation and narrowing of the river course with suitable abutments as we argue in the section 'Addressing the endogeneity of dams – geology and dam placement' in the main text), but also where there is potential for canals, either directly at the dam site or from the natural river course below the dam, that could command irrigable land at reasonable cost.

Appendix 2 Figure 8 also shows these dams in relation to administrative units; the first dam on the 370m contour commands, potentially, much of the district in which it is located, and potentially much of its downstream neighbour (provided a canal was built on its left bank). But dam 2 in the same district on the 270m contour commands only a portion of its own district (Jalgaon), and less of its downstream neighbour (Dhulia) than (potentially) dam 1.[133]

A further feature to note from **Appendix 2 Figure 8** is that the watershed of the Tapi cuts across several districts, including Nasik and Aurangabad. Other points of interest are that, when drainage channels (streams and rivers) on which dams are located are identified, many (rivers) form large sections of borders between districts, as noted by Strobl and Strobl.

Use of Pfaffstetter units

Hence, while *not all dams* in districts disgorge into the same neighbouring (downstream) district(s), the potential advantage of using Pfaffstetter units is that *all dams in an odd-numbered upstream unit* do indeed disgorge into and through the next lower *odd*- numbered unit (at the same level); but dams in even-numbered units may barely traverse the next lower odd- or even-numbered unit. In terms of upstream (Pfaffstetter) units Strobl and Strobl are not entirely clear whether these are neighbouring upstream (higher numbered) units, or all higher numbered units (2011, pp 436, 441). Table variable 'UDAMS' are 'Dams upstream' (it is not stated whether these are in neighbouring Pfaffstetter units), 'UDAMS(U2)' are 'Dams further upstream (one level)' and 'UDAMS(NB') are 'Dams in neighbouring but non-upstream areas' (p 441; see also p 443 fn 41).[134]

However, for neither Pfaffstetter units nor districts can it be confidently expected that a dam in the immediately higher unit (as used in Strobl and Strobl's data construction (or neighbouring upstream district [135]) will command a majority or even a substantial portion of that lower (downstream) unit.

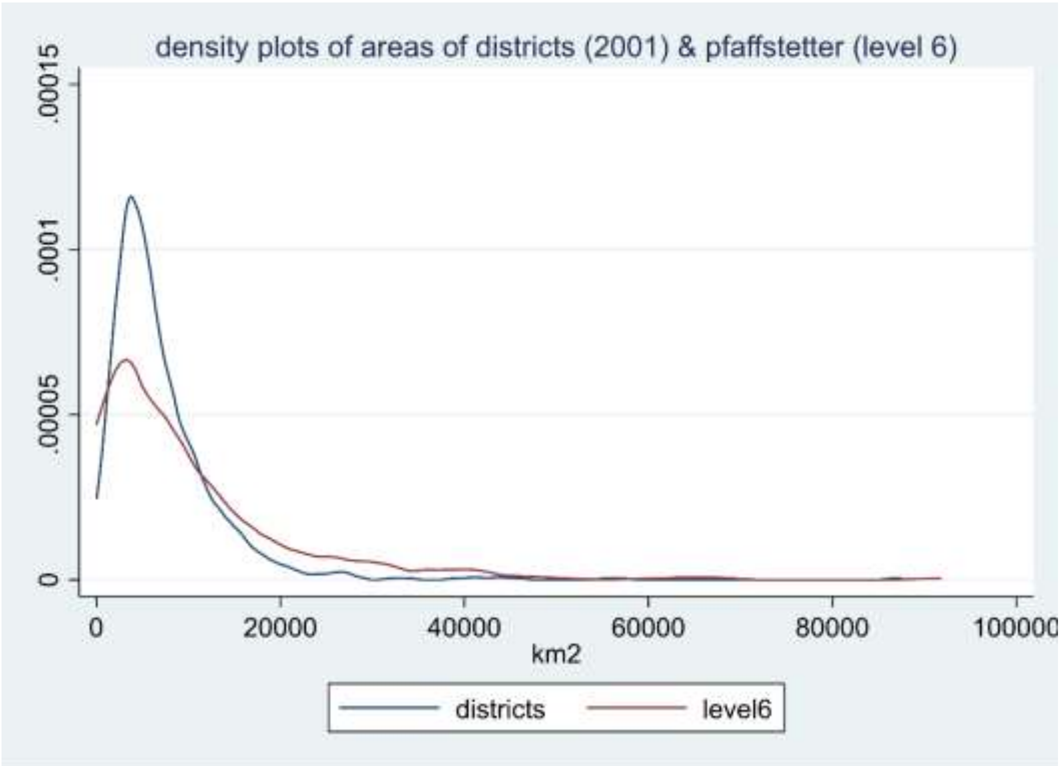
Hydraulic units have the further disadvantage that potential outcome variables are restricted presently to remote sensed information based on NDVI images. Districts or other administrative units can have numerous potential outcome variables derived from census or

[132] This argument depends on the contours that are not drawn here but can be provided by the author.
[133] Common sense suggests that the potential effects of dams will attenuate with distance, and this attenuation will be less for larger dams (see Rufin et al, 2018).
[134] "Each basin is then assigned a Pfaffstetter 6-digit code which allows one to determine whether it is upstream, downstream or not related to another basin in the data set"; but as we have seen, being in a one number higher Pfaffstettter unit at the same level is not very informative as to whether the units are Bishop or Rook neighbours, depending on whether the neighbours are both odd or even or odd and even.
[135] **"W**e made the assumptions that dams were generally not located exactly on the border of basins and that the catchment area was usually contained within a dam's own vicinity" (Duflo and Pande, p 436).

administrative data, or from surveys, which are often produced to represent administrative units.

Pfaffstetter units also vary greatly in size within a given level rather more than districts (**Appendix 2 Figure 9**), depending mainly on the size of the basin within which they are contained; large basins tend to have larger Pfaffstetter unit areas, making it likely that smaller proportions of these larger units may be affected by any dam.

Appendix 2 Figure 9: Size distributions of districts and Pfaffstetter units



Area-based units of analysis: discussion

Thus, to repeat, while dams in districts may disgorge in different directions, all those in hydraulic units disgorge into the same downstream Pfaffstetter units, but this does not mean that they command meaningful areas in lower numbered units, but may command areas in higher numbered units. Moreover, both districts and Pfaffstetter units have the unfortunate characteristic that the majority of dams (actually upstream) in an upstream unit potentially command only a portion of their downstream units (or indeed of their own unit), and even this command is dependent on investments in canals and command areas, and or pumping. Downstream units (districts or Pfaffstetter) may have many hydraulically upstream dams, but little commanded area that is suitable for irrigation.

Measures of the area with potential for irrigation downstream

In principle it would be convenient if the potential impact of a dam in a downstream unit could be defined by the share of that downstream unit that is potentially commanded by the dam (and is otherwise suitable – non-urban, irrigable soils, and so on). In this case, in order to regress the impact of a dam on such an area, one could weight the capacity of the dam by some measure of the portion of the area in which the dam could have a potential impact (as well as other factors), rather than use a measure that implies that the impact of the upstream dam could be uniform over the whole of the downstream unit. It is obvious for example, that a dam on the lower border of a unit where the river disgorges to the neighbouring downstream unit could not generally enhance irrigation within the unit in which it is located, whereas a dam near the upper border of its own unit would probably command a higher portion of its own unit. The dam near the lower boundary of its own unit is likely to command more of the unit into which it disgorges (and subsequent downstream units).

Furthermore, dams may command (by gravity) areas in units that are not defined as downstream in either the sense that their drainage passes into or at least along the border of that (downstream) administrative or hydraulic unit. This occurs because canals can (and indeed are needed to) transfer water into areas of neighbouring units, whether 'downstream' in the drainage channel sense or not, that are lower than the off-take of the dam (and allowing for suitable slope in the canal to enable hydraulic flow). This is obvious with the use of administrative areas which are not aligned with hydraulic units. But it also occurs with hydraulic units. Thus, we can see that in the Tapi basin (**Appendix 2 Figure 8**) a dam in the upper reaches of Pfaffstetter unit 453802 can easily irrigate areas in its 'upstream' neighbour 453803.[136]

Hence, both these approaches have a number of limitations which are likely to result in noisy estimates (Duflo & Pande, p 629) not only with regard to downstream impacts but also within their own districts. As Duflo and Pande note, dams may cause disruption during their construction and when filled around the dam site and to the area impounded. They may also have effects further upstream if restrictions on land use are imposed in the catchment areas, in order, say, to reduce silt run-off. Duflo and Pande suggest that upstream impacts are broadly limited to the district in which a dam is constructed, but this is clearly not always the case. Impounded areas are often small compared to district areas, but the impounded area stretches upstream within the river valley and may extend beyond the district of the dam. However, land-use restrictions placed on catchment areas may be much more extensive, extending up to the (generally) steeper slopes of the watershed. It may be in those areas, often less populated and often, in the Indian case, populated by tribal (discriminated) groups it is easiest to place dams, and displace populations. The correlation between the number of dams in a district and the proportion of the population (1971) that is tribal is 0.18 ($p < 0.01$, in the agricultural sample of districts[137]).

In neither case ('Dams' or Strobl and Strobl, Blanc and Strobl) is there a quantitative assessment of the extent to which dams in either type of units could actually 'command' areas in their own units, or in 'downstream' units; nor do they assess the geographic distribution of upstream catchment or impounded areas. 'Dams' takes no account of the fact that not all dams disgorge into the same downstream neighbours. It is obvious from the examples given that, for both units, many dams cannot actually have effects on much of the putative downstream units, and many dams may have very little possibility for downstream effects in their own unit.

[136] Thus the Upper Erode Dam in 453802 potentially commands larger areas in 453803; however, this dam is part of the larger Perambikulam-Aliyar 'basin' project (PAP) dating from the late 1950s to 1970s, which involves "Storage and diversion works on the eight rivers with interconnecting tunnels hav[ing] been constructed. The tunnels divert the waters impounded in the reservoirs to the plains of the Coimbatore and Erode district of Tamilnadu falls in Cauvery river basin and Chittoorpuzha area of the Kerala States". PAP-report-24.07.17.pdf [available at https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjjoYOupLnuAhU1RRUIHdV8CF8QFjAQegQIBhAC&url=http%3A%2F%2Fnwm.gov.in%2Fsites%2Fdefault%2Ffiles%2FPAP-report-24.07.17.pdf&usg=AOvVaw1AhQI-DE1oTxodvx0zhTSI]. Accessed: 26 January 2021. See also https://sandrp.in/2020/10/05/reservoir-operations-fail-people-in-chalakudy-river-basin-in-kerala-in-2020/#more-38281. In this project Palakkad District in Kerala is categorised as upstream of Coimbatore, although all rivers in Palakkad flow west to the Arabian sea, while all those in Coimbatore flow east to the Bay of Bengal. This can only be included in district or Pfaffstetter area-based analyses by inserting the inter-basin links. There are other west–east inter-basin transfers down the length of the Western Ghats.

[137] Duflo and Pande's dataset has the wrong tribal share in many districts apparently due to mis-merging of data sets; in their data $r = 0.10$, $p = 0.08$.

Dams, command areas and canals

A better definition of whether a dam is upstream of a district, in the sense that it has hydraulic effects on the district, given the three major pathways by which effects take place, is to trace both the downstream hydraulic pathway and the routes of canals fed by the dam (directly or indirectly). One way to do this without access to detailed canal data would be to trace the area commanded by the contour at the point of outlet from the dam to a canal (base of dam plus height to canal intake) that commands (parts of) the district to potentially irrigable areas (areas with suitable soils and topography). Ideally this (sloping) contour would allow for a slope required for water to flow under gravity. The geology and topography of the area between the dam and potential command areas would both physically constrain and determine the costs of any canal and hence any potential command areas. For example, steep rocky slopes on the contour might prohibit or certainly raise the cost of any canal. In some cases tunnels can be built through or around difficult geological structures, even allowing water into other river basins, As, for example in the Periyar–Vagai and Parambikulam Aliyar (Kerala -> Tamil Nadu), Kurnool Cudappah Canal (between the Krishna and Pennar basins in AP), the Telugu Ganga Project (from the Krishna in Srisalilam District to wards in Chennai , Tamil Nadu and the Ravi–Beas–Sutlej (which diverts water from western sub-basins of the Indus to the eastern sub-basins) systems constructed starting in the 19th century during the colonial period. In practice, while there are relatively few of these few schemes, the Ravi-Beas-Sutlej and its extensions, especially in the Bhakra system post-Independence, accounts for a significant proportion of the potentially irrigated area in India. However, this would be computationally demanding. I have not attempted these computations (yet).

An alternative is to use existing data on command areas developed for irrigation and link them to dams. Unfortunately, although some data on the dams linked to major command areas exist, they are probably incomplete and possibly misleading. This raises the question of whether dams are likely to have meaningful effects outside districts which they hydraulically command. Nevertheless, it is possible to add district-level variables that represent the areas irrigated by command areas to variables representing the river-course hydraulic pathways from dams to districts.

Unfortunately, this approach is limited by the sparse information on the dates at which canals were developed and the times and amounts of water made available in districts; as with dams, the date of completion of a canal may not mark the time at which water became available, since actual utilisation of canal systems has been a perennial problem in their management.

Do canals lead to impacts in districts not hydrologically downstream?

With the exception of the inter-basin projects, especially those of the Ravi–Beas–Sutlej–Bhakra and Periyar–Vaigai systems, it appears that most districts with command areas nominally commanded by dams are included in the hydrologically downstream districts of those dams (details available from the corresponding author). But as illustrated in our discussion of links between command areas and dams, neglecting the Ravi–Beas–Sutlej–Bhakra systems means that areas which putatively benefited massively from dams in the 1971–99 (and previous and subsequent) periods are not included in the analysis of the effects of dams.

These and similar considerations imply that, in principle, account should be taken of the canal systems developed to exploit dam capacity developed in any period when trying to assess the impacts of dams. We do this in some analyses by including as a separate variable, a variable reflecting the area under irrigation command areas but not linked to any dams; it is not a very good way to deal with this problem.

Neighbours and hydraulic direction

There are clear limitations to any hydraulic definition we have employed linking dams to their hydraulic effects in neighbouring districts. In addition to the issues already raised, any such model of 'upstreamness' would be obviously unsatisfactory for modelling the possible upstream/downstream relations of dams because of the known influence of human intervention to deliberately modify not just the timing of hydraulic flows (dams) but also their spatial distribution (canals and tunnels, etc), unintentionally (rail, roads, housing, embankments) or in unintended ways (groundwater flows). The hydraulic definition we employ entails all upstream/downstream/both/neither relations between districts to be within the same river basin. This entails additional issues when districts comprise more than one river basin, such that not all dams in an 'upstream district' are in fact 'upstream', and where only parts of districts are in fact downstream of those dams that are upstream. There is quite a high correlation between 'dams actually upstream' in an upstream district and 'all dams in a district that has any dams upstream'. Nevertheless, the geography of those parts of a district that are actually upstream may be quite different for different river (sub-)basins of the district.

A further issue is that in some cases a single or a few dams in a very small area of a hydraulically upstream district may define that district as upstream. For example, one dam in Jalgaon is upstream of a very small part of Nashik. Similarly, a small number of dams in Nashik are upstream of small parts of neighbours Dhule and Thane, while most dams in Nashik are upstream of either Jalgaon, Ahmadnagar or Aurangabad (Maharashtra) (Appendix 2 Figure 4); more than a few are upstream of Valsad. The topography of Nashik in the areas upstream of Valsad and Thane is quite different from those areas upstream of Jalgaon, Aurangabad and Ahmadnagar; the west flowing river basins contain more of the steeper, more dissected west facing slopes of the western Ghats compared to the more moderate slopes of the east flowing river basins on the gentler slopes of the western Ghats in their rain-shadow.

Perhaps the most important of the interventions that determine most of the irrigation related effects of dams are canals (and tunnels), mainly for the purpose of conveying stored water to areas suitable for irrigation. Such inter-basin transfers are most important for the mega dams which store most of the water so, even if there is only a limited number of cases, these dams and the canals linked to them could have disproportionate effects. Canals can also be important in transferring run-of-river water into districts that are not hydraulically downstream using the definition described, as, for example, in some of the older canal systems such as the Jamuna and Ganga canals.

Such inter-basin canals drawing water from river flows are important for many districts included in the huge irrigation systems of northwest India (but also elsewhere). These districts do not appear as hydrologically downstream from some of the largest dams constructed in the post-Independence period, some being completed in the period covered by 'Dams' (1971–99).[138] They are also important where irrigation schemes derive water from dams whose river course does not make the district in which the dam is located upstream.[139]

What is so special about neighbours?

There is no need to attach special significance to neighbouring districts (or Pfaffstetter units), and doing so does not make much sense, given that all dams in neighbours having one or more dams that are hydraulically upstream may not be upstream, and those within

[138] For example, the Pong and Pandhoh dams.

[139] A significant example is the relation between the districts of Saurastra and Kachchh receiving irrigation water from the Narmada dams with which they have neither contiguity nor hydraulic relations; other examples are those districts drawing water from inter-basin transfers from the Indus to the Ganges/Jamuna basin.

neighbours which are hydraulically upstream may not command much area within their downstream neighbour.[140] A focus on upstream neighbours could be very misleading. Instead, we can assess the likely effects of dams by their size,[141] the distance within and along the border of their downstream river course, attenuated by the (inverse of the) distance from the dam to the district, and a measure of the area within a district that could be commanded by the dam.

We can combine both approaches of course, by differentiating dams hydraulically upstream in neighbours from dams that are upstream of neighbours.[142] We have done this, but the variables created do not correspond to the variables constructed for 'Dams' and our variables reflect hydraulic realities, not those underlying the designation of neighbours and their types in 'Dams'. Because a focus on neighbours makes no sense we do not report any of these neighbour variables or results using them.

However, our approach does not take full account of the potential of canals (and the need for them in many cases) or pumping to actually command areas that are not within the river basin of the dam. Canals enable not only command of areas downstream within the same river basin but of those in neighbouring basins, or even non-contiguous river basins.

[140] It is the same with Pfaffstetter unit neighbours.
[141] See elsewhere, where I assert the importance of taking the size of dams into account; more than 80% of the effective capacity of dams is provided by less than 10% of the dams. A study of the effects of numbers of dams, given this very left-skewed size distribution, is unlikely to have much to say about the effect of dams, and is likely to be confounded by uncontrolled characteristics of districts in which there are many dams. This, and the challenges of identification of the effects of dams, is discussed in the section ' 4.4 Addressing the endogeneity of dams' in the main text.
[142] And in principle one could assess the area with the district that is hydraulically commanded by the dam.

Appendix 3: 'Dams''s justification of districts as units of analysis in

In this appendix we discuss the justification given in 'Dams' for using district-level data to analyse the impacts of dams. The examples quoted do not support the assertions made.

The text of 'Dams' justifies the use of districts as units of analysis on the grounds that

> The absence of data on the geographic extent of the catchment and command areas of large Indian dams prevents us from identifying the fraction of district area covered by the catchment and command areas of each dam. Available catchment and command area maps suggest that the district in which the dam is physically located usually contains most or all of its catchment area, even for large dams." [fn 7]. Some examples are Chari et al [1994] and Chari and Vidhya [1995], [fn8]. See again Chari and Vidhya [1994, 1995], Chakraborti et al. [2002], and Vidhya et al [2002] for specific examples. However, there are instances where the command area covers districts that are not downstream. In personal correspondence, John Briscoe (until recently the Bank's senior water professional and spokesperson on water issues) offered one example: The command area of one of India's largest dams, the Bhakra Nangal dam, covers part of the district lateral to that in which it is built (Chakraborti et al [2002], and Vidhya et al) [2002] (p 610).

The references do not support the claim.

If 'Lateral' should be interpreted to mean 'in another river basin', the example of the Bhakra dam and the Bhakra–Beas canal system is far from trivial as it covers large proportions of Punjab and Rajasthan states.

Duflo and Pande refer to several publications to justify their claims ("Some examples are Chari et al [1994] and Chari and Vidhya [1995], Chakraborti et al [2002], and Vidhya et al [2002]"). But these sources do not seem to provide justification for the assertions made.

It is not clear which sources for these publications Duflo and Pande refer to (they are unpublished but may be found online); Chakraborti et al (2009), in a similarly titled online paper (accessed in November 2020), report that "Nagarjuna Sagar Left Canal (NSLC) command is designed for irrigation of 0.42 million hectare CCA in 3 districts in Andhra Pradesh State". The NSLC is fed by the Nagarjuna Sagar dam, which is a combined irrigation and hydroelectricity dam in Guntur District in Andhra Pradesh (now in Telengana State). There is also a right bank (Jawahar) canal (as is suggested by the existence of a 'left' bank canal), supported by the Nagaranja Sagar dam. In addition, the Alimineti Madhava Reddy lift irrigation canal pumps water from the Nagarjuna Sagar dam (and potable water is supplied to Hyderabad city). Even though Guntur is a coastal district and therefore less likely to have many downstream districts, the Nagaranja Sagar dam actually serves areas in five districts – Nalgonda, Khammam, Krishna, Guntur and Prakasam. The catchment of the Nagarjuna Sagar Dam includes at least 35 (1981) districts in three states; only 0.4% of the catchment is in the dam's own district of Guntur (author's GIS).

The title of the paper by Chari and Vindhya which Duflo and Pande cite refers to the 'Salandi Command Area'. The Salandi dam in Kendujhar district in Odisha serves the Salandi Major Irrigation Project and the Bidhyadharpur and Anandpur Barrages, with effects in Baleshwar, Bhadrak and Kendujhar districts. Its catchment area is mainly in Mayurbhani (87%), rather than Kendujhar (13%), the district of the Salandi dam.

Another set of authors to whom Duflo and Pande refer for their claim that command and catchment areas are in the same district as the dam are Vidhya et al, whose paper's title refers to the Bhadra dam; in an article with the same title there is no reference to the districts in which catchment and command areas fall. The Bhadra dam is in Chickmagalur district on the border with Shimoga; its catchment is almost entirely in Chikmagalur with a small portion in Shimoga (0.1%). WRIS data report that this dam affects three districts (Shimoga, Davanagere, Chikmagalur) through canals, but may have effects through modified river flows and groundwater in the 30 districts downstream through or along the borders of which it passes; just 0.02% of the downstream river length is in the district of the dam.

Appendix 4: construction of topography and geography variables

Here we describe our reconstruction of the topography and geography variables used in 'Dams'. We use what appear to be the same or very similar sources and methods as the paper's researchers, and generally our results for geography and topography variables are very similar, except for those districts which do not correspond to those of the 1991 set of districts apparently used in 'Dams', and for the river variables[143]. Since a district boundary map is used to construct topography and geography variables where our boundaries are likely to differ, the geography and topography variables are also likely to differ. As explained elsewhere, it appears that 'Dams' took the values of these variables for the 1991 district boundaries of districts of the same name, ignoring areas which were split off from (or amalgamated) in the formation of these districts between 1961 and 1991. We have not checked every such case, but those we have checked conform to this pattern.

The geography and topography variables are constructed from overlays of vector districts or river trace files on raster files of or derived from a DEM file. We describe which district and river trace vector files are used; 'Dams' is not clear which files were used for the district boundaries, and the source for a DCW river trace file referred to is no longer available, although copies, which may or may not be identical, are available.

After describing the vector files, we briefly describe how to extract the geography and topography variables and how we think these variables in the 'Dams' dataverse files were constructed.

4.1 Districts

Our construction of district boundaries is described in the main text in the section 'Which districts and rivers?". Essentially, we allocated *taluk* to districts which correspond closest to the maps for the different periods in the Indian Administrative Atlas (IAA). Thanks to distortions and errors in the IAA maps and our digitisation of them, there may be errors in our allocation of *taluk*; in a few cases *taluk* may have been subdivided, but we believe any resulting errors are minor. We prefer this approach to the use of "super-districts" described by Asher et al., 2021, because the latter are larger and more heterogenous.

The World Bank dataset of districts does not correspond to either the 1961 or 1971 Indian Census districts, in that Surat (the 1961 district) is divided in WBAg data into Surat and Valsad, a division which occurred in 1966.[144] Other subdivisions of districts between 1961 and 1971 are not relevant because they are either not present (Sangrur into Sangrur (Punjab) and Jind (Haryana); Hoshiarpur to Hoshiarpur and Ropar (both in Punjab); and Chandigarh from Patiala in Punjab; Ongole from Guntur and Nellore in Andhra Pradesh) or are in states not included in the WBAg data set.

4.2 River traces

As noted, the district river variables (average and categories of slope, and river length) in 'Dams' are not correct. 'Dams' reports that "Data on… river kilometers… and river gradient are collated from two GIS files: *GTOPO*30 (elevation data, available at http://edcdaac.usgs.gov/gtopo30/gtopo30.html), and 'dnnet' (river drainage network data,

[143] We use 'Dams' assignment of neighbour type to districts in reconstructing geography and topography variables of neighbours. There is no point in attempting to correct these assignments as there is no "correct" assignment of "type" to neighbours.
[144] Gandhinagar also became a district between 1961 and 1971, taking areas from Mehsana and Ahmadabad, but Gandhinagar is not in the WBAg dataset.

available at http://ortelius.maproom.psu.edu/dcw/). … For river gradient we… restricted attention to polygons[145] through which the river flowed" (2005, p 31).

There are some problems in reconstructing river slopes from the original sources reported by Duflo and Pande. The data source for the river traces (the dnnet polyline from the Digital Chart of the World) is no longer available from the exact source listed. However, various other sources provide DCW dnnet or equivalent polylines. There are several of these, and we try several different sources and constructions of river polylines.

There is also a significant problem with the dnnet polylines for the purpose of extracting river slopes,[146] namely that for lakes (natural or impounded water bodies behind dams) and wide braided rivers there are lines for both sides of the river for some reaches, (and also for islands within the banks of the river), but none for lakes (or reservoirs). Compared to a single centre line a somewhat different set of cells may be chosen using these files to compute average or categories of river slope. In these DCW nnet files some braided areas and lakes/reservoirs are contained in a separate polygon features file. Other sources of DCW dnnet contain all rivers in the polyline feature. It is not known whether the source used by Duflo and Pande contained the polygons or the braided lines, and if it did not contain these whether centre lines or polygons were added back in to extract slope cells.

Recognising the problem, there is a source (see Appendix 3 Table 1) that provides centre lines although this source does not entirely replace all missing river traces in the other sources that we have. It is not clear that this source was used by Duflo and Pande.

Appendix 3 Table 1: Sources and availability of river trace GIS files

Source	All traces in one coverage	Small rivers	polygons	Centre lines
Dnnet pre 2005	No	yes	Available	No
Dnnet 2005	Yes	Yes	Yes	No
Dnnet 2016[a]	Yes	Yes	Yes	No
NE center lines[b]	no	No	No	Yes

a. currently (early 2022) available from http://www.diva-gis.org
b. https://www.naturalearthdata.com/downloads/10m-physical-vectors/10m-rivers-lake-centerlines/

4.3 Elevations

We use the GTOP30 DEM files extracted for the all-India and various district boundaries.

4.4 Slopes

Slopes are computed from the GTOP30 DEM using ArcGIS Pro.

[145] The term 'polygons' is normally referred to as 'pixels'.
[146] One overlays a river trace on a grid of cells reporting the slope in each cell to extract those cells through which the river flows. The slopes of all the cells extracted from a district because they are overlaid by the river trace provide the average river slope; the cells can be categorised into groups (0-1.5 degrees, 1.5-3.0, etc.). This is not the only way to compute average or categories of slope, but it is the one reported by Duflo and Pande and is commonly used; the most obvious deficiency of this approach is that it is not directly - weighted by river size.

District slopes

We extract district slope categories using the district boundaries we constructed as described above.

River slopes

We constructed different river length and slope geography and topography variables using the different river trace and district boundary vector files described above; our preferred river traces are the HydroRIVERS 15 arc second files for Asia (https://www.hydrosheds.org/products/hydrorivers).

Appendix 5: Vegetation Index and agricultural productivity – AVHRR NDVI calculation and validation

The agricultural production variables in 'Dams' has several deficiencies. It is not only spatially and temporally biased, as reported above, but also does not include several major crops characteristic of areas with many dams.

Further deficiencies of the agricultural production variables in 'Dams'

The measures of agricultural production ("prodmain" and its log, and the water and non-water intensive crop production aggregates) in 'Dams' only uses six of the crops for which observations are available in the WBAg data[147]. These crops constitute about 75% of the value of production (at 1960-5 average prices) of the 18 crops for which production and price are available, and are generally among the 4-5 most valuable of these 18 crops. Bhalla and Singh, 2011, district data include 35 crops in their "val_35" variable. It is not possible to directly compare the total value of the "prodmain" and "val_35" variables as there are no common prices ('Dams' uses 1960-65 prices, Bhalla and Singh, 2011, use 1990-3 prices), and they cover different geographical units (districts) and areas (WBAg data do not include Assam, Kerala, Himachal Pradesh, Jammu & Kashmir, for example).

We can, however, compare the values of the 19 crop totals in the UMD district agricultural data which covers 1960 -1981[148] which report the value of crop production aggregates published in Bhalla and Tyagi, Patterns in Indian Agricultural Development, 1989, using 1971-2 prices[149]; the 19-crop aggregate includes all the crops in the WBAg data, and the 37-crop aggregate includes all those in the Bhalla and Singh 35-crop aggregate.

Comparisons at state level show that the ratio of 19 to 37-crop output totals averaged over 1970-73 crop seasons, varies from 23% (Kerala) to 100% (Manipur); as expected for the states with lower proportions of irrigated areas (Rajasthan), and those states predominantly in the Indian Shield (Gujarat, Maharashtra, Madhya Pradesh, Orissa, Karnataka, Andhra Pradesh, Tamil Nadu), the ratio of the 19 to 37 crop totals is lower than in states of the Indo-Gangetic plains (Punjab, Haryana, Uttar Pradesh, Bihar, West Bengal). In the less abundantly irrigated states the ratio of the 19 – 37-crop aggregates generally falls below 90% whereas for the more irrigated states it is nearer to 99%. This suggests that the 6 crop production variable in 'Dams' comprises only 60-70% of the value of agricultural production.

The most significant crops that are not included in the 'Dams' agricultural production aggregate are groundnut and pulses one or both of which feature among the 6 crops with the greatest value in most periods (see Appendix 5 Figure 1).

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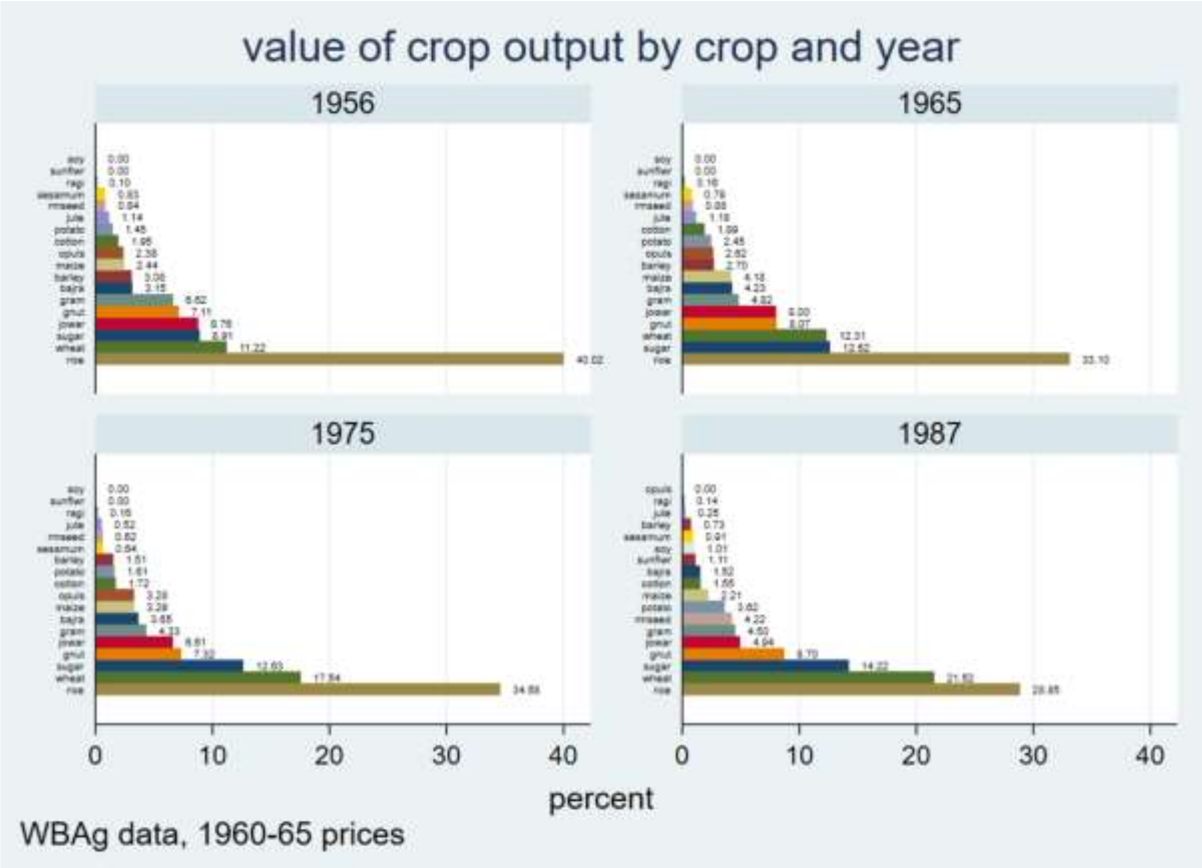
[147] Among other problems with this data set is that it lacks data for several large states, and it is not entirely clear what the boundaries of the districts it does report actually are for the variables it contains (see further in Appendix 5). Nevertheless, comparison of variables that are also in the Bhalla and Singh data for the same periods have quite high correlations (for example, gross and net cultivated and irrigated area – we use the original WBAg data where the dataverse 'Dams' data doe not include them), simple correlation coefficients are >0.81), and grow at similar rates over time (results available on application to the corresponding author). The B&S data have slightly higher correlations with the AVHRR VI that we use in this work than the WBAg data, for the period common to both data sets (1981-1987). This association is not so high for the WBAg production variables extended by the authors of 'Dams' (1988-1999), but can be computed only for those districts present in the extended WBAg dataset. One reason for the less satisfactory association of the 'Dams' agricultural production data with B&S data is that in the 'Dams' data agricultural production can be computed for only 6 crops, while the B&S agricultural production aggregate includes 35 crops. Using the value of all the crops (18) available in WBAg up to 1987 improves the association with B&S somewhat. The remote sensed AVHRR VI variable described below does not distinguish among crops, of course. One problem in making these comparisons relates to the different construction of districts in B&S from what we infer was the construction of districts in the original and extended variables in WBAg. B&S use "composite" districts with quite consistent boundaries over time; some of these notional districts are quite large especially in Punjab/Haryana, and in Andhra Pradesh. We collapse (aggregate) WBAg districts to B&S composite districts, and collapse Sangrur and Jind, and Hoshiarpur and Ropar in the B&S data, as it seems these districts are combined as pre-1966 districts in the WBAg data.

[148] University of Maryland, Indian District agricultural data set (1961-1981), downloaded in the late 1990s. This source includes a 37 crop aggregate.

[149] This is a forerunner to Bhalla and Singh, 2001 and 2011.

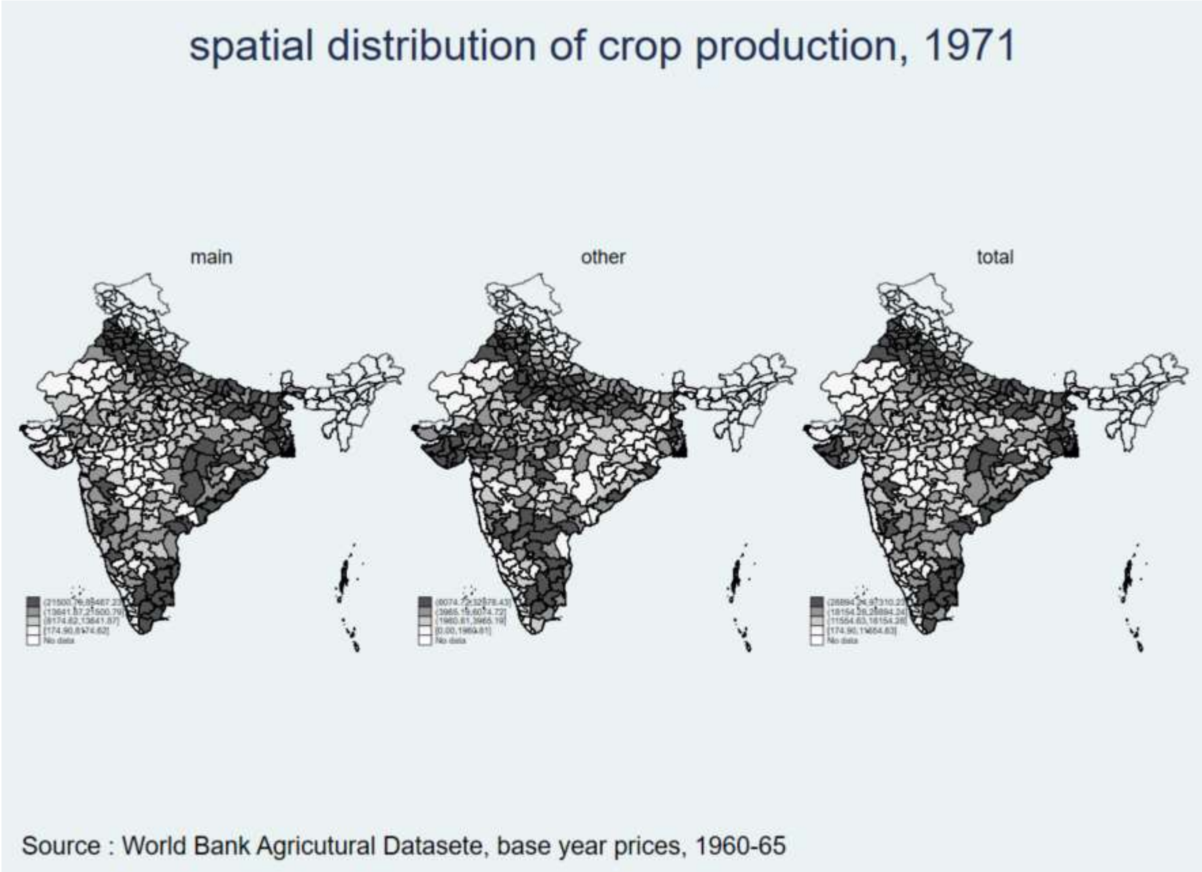
Appendix 5 Figure 1: Value of crops in WBAg data set by period.



It is of course immediately notable that some of the “significant” crops that have been excluded (groundnut and pulses) are more characteristic of the largely rainfed Deccan plateau areas where dams are concentrated. Hence, it not unlikely that the spatial distribution of production of the “other” crops is different to that of the crops included in the outcome variable deployed in ‘Dams’, as Appendix 5 Figure 2 confirms, and is likely to be biased against districts in which there are many dams. It is unclear why the possibility of spatial bias in the agricultural production variable used in ‘Dams’ was not (and has not previously been) commented on.[150] We do not pursue using the value of all crops in the WBAg data here, because this variable is available only up to 1987 (and does not include the wider range of crops available in Bhalla and Singh’s district agricultural production data.

[150] Another issue that might be raised about the value of production variable in ‘Dams’ is the use of average prices immediately pre-green revolution, when it is known that major crop prices changed somewhat after the change in policies associated with this period – increasing support for major GR crops wheat and rice. Using 1970-5 average prices, for example, reduces the rate of growth of the value of the “other” crops between 1960 and 1987.

Appendix 5 Figure 2: Spatial distribution of value of production of "6 major" and other crops in WBAg data set used in in 'Dams'**, 1971**



AVHRR and MODIS VI (SHRUG) NDVI and Bhalla and Singh productivity

Vegetation Indexes can be used as proxies for the sorts of land productivity effects of dams it is reasonable to assess (Strobl & Strobl, 2011), but they need validation. In their data appendix Asher and Novosad (2019; see also Asher and Novosad, 2020, Asher et al. 2021) use four variables to validate their NDVI/EVI variables (proportion of land irrigated, land suitability, estimated consumption, and District Domestic Product – DDP), none of which directly reflects agricultural productivity.[151] We use estimates of district-level agricultural production from Bhalla and Singh as support for using the NDVI variable we compute as a proxy for agricultural productivity, and we show that our VI performs better than the SHRUG variables. While the periods over which these NDVI series are available only partially overlap, our NDVI performs better than the NDVI/EVI

[151] We do not here compare our VI with the 'irrigation share' of village area reported in Asher and Novosad's (2019) Online Appendix Tables A1, and A2. This variable was computed from the Socio-Economic Caste Census of 2011, which was scraped from the SECC website. It is not clear why this variable was used rather than a similar variable that could have been computed from the 2001 (and 2011) Indian Census VDs. The VD contains variables for 'total irrigated' and 'total unirrigated' land areas, as well as irrigated areas by source. The SHRUG database has a file with a variable 'any_irr_acre_ share', which seems to have been used in the two tables referred to. For those villages we can match with the 2001 VD there is a correlation of higher than 0.48, but we cannot match a large proportion of villages. These irrigation share variables seem to assume what they need to establish; irrigation is only a proxy for agricultural growth and it is known that different types (canal, groundwater, etc), and locations (mainly geological structure) of irrigated areas affect its productivity. Land suitability is also a variable that assumes what it needs to establish, since it does not directly reflect the value of agricultural production. Consumption is -based on a small area estimation combining survey with census variables to predict village consumption; the parameters and estimation details are not readily available. While consumption is a potentially useful portmanteau variable, it neither reflects wellbeing (since (the value of) consumption may not translate in a straightforward way into wellbeing in the same way in all locations), nor the presumed immediate effects of irrigation on agricultural production (dams can of course have positive and negative effects on well-being through other routes). District domestic product is drawn from an Indian government source which is no longer available; we discuss this variable below.

variables deployed by Asher et al (2020) in relation to the agricultural productivity variable for 2005-8 in Bhalla and Singh.

We also compare our NDVI with those in the SHRUG database.

In order to prepare validation variables similar to Asher and Novosad, 2019, I first intersect CEISIN (2001) village centroids with Bhalla and Singh districts, and capture the VD attributes reported in the CEISIN GIS files; these attributes are extensively cleaned.

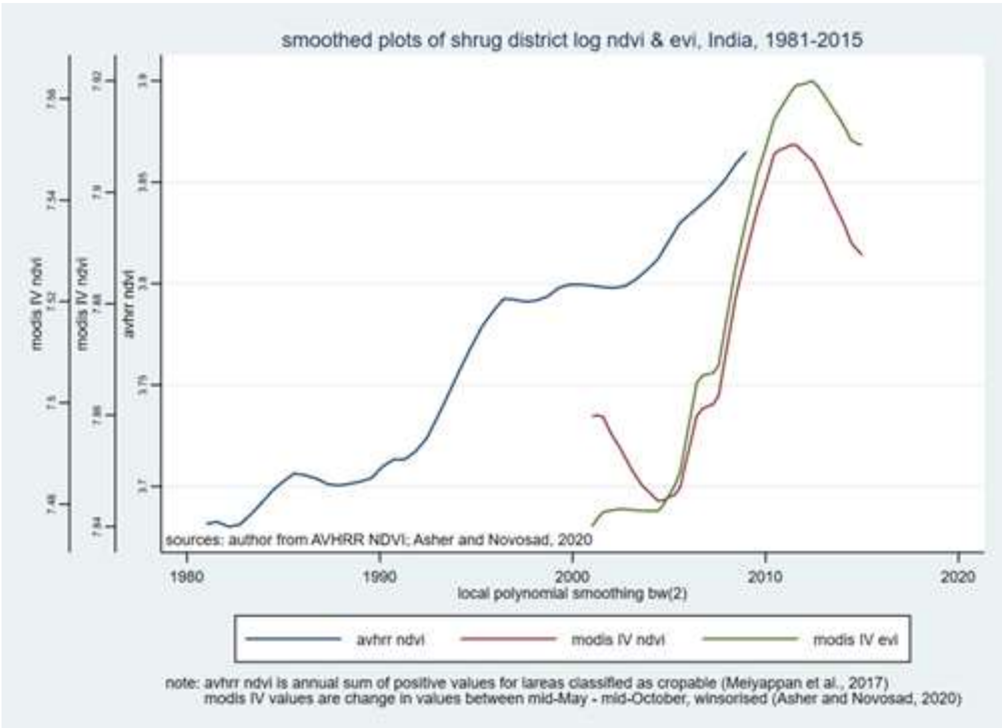
To join these village variables to the SHRUG villages, I merge this file with the SHRUG keys and then to the SHRUG NDVI/EVI variables. These village records are then collapsed to Bhalla and Singh districts (area-weighted NDVI/EVI). Note that the correlation between VD area and GIS estimated areas is not good, so it is not clear how much confidence one can have in village area normalised Village Directory variables. This file can be aggregated to Bhalla and Singh districts or SHRUG super-districts.

District-level agricultural productivity and VIs

First, we compare the VI indexes with each other, and then the VI indexes with the 35-crop productivity variable computed from the Bhalla and Singh data. The association of the VIs is not good, as can be expected from the different ways in which they are computed (the sum of positive values over the whole year (our calculation) vs differences between values in mid-May and mid-October (Asher et al, 2021).

Appendix 5 Figure 3 shows the time pattern of average SHRUG district VIs; clearly the different VIs are available for different periods, but overlap between 2000 and 2009. Starting around 2001 the AVHRR VI rises steadily from its plateau during the late 1990s to the end of the series. The MODIS NDVI and EVI VIs from SHRUG rise more or less steadily from about 2003 to 2012 and then fall. There is no account given for this decline.

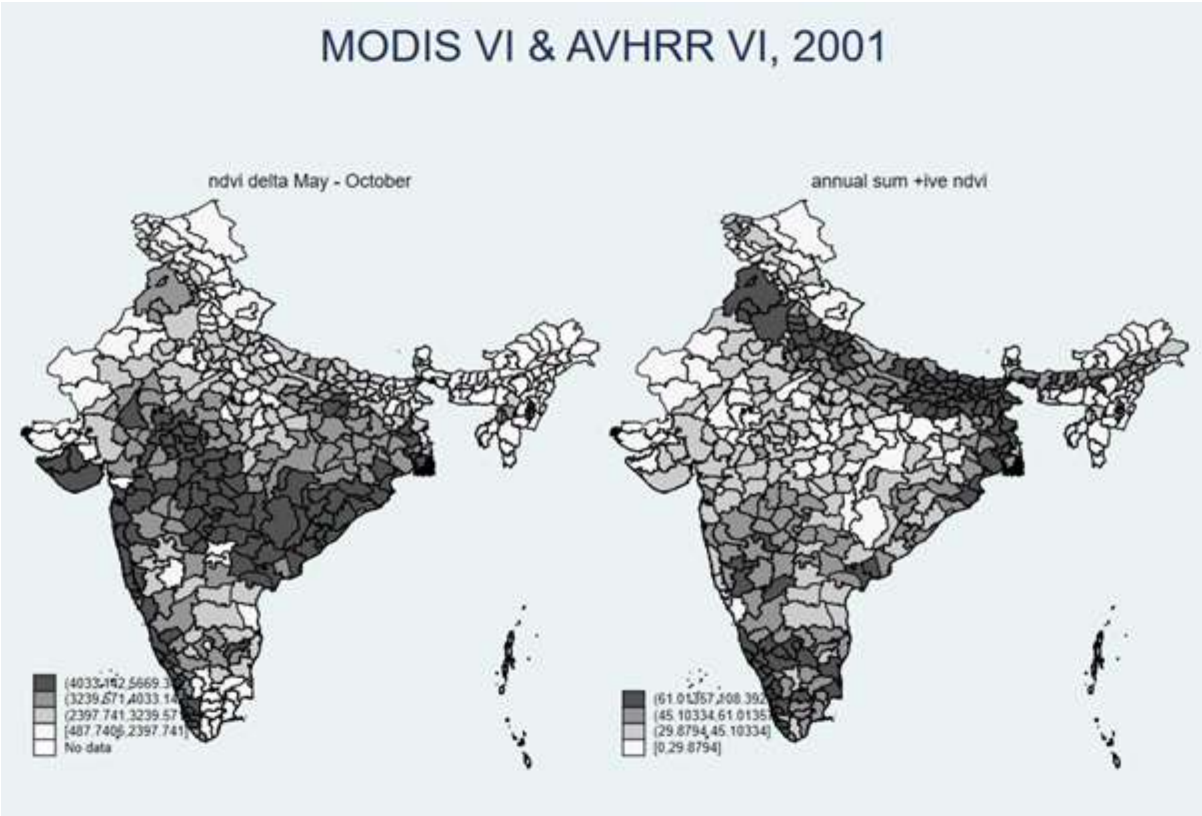
Appendix 5 Figure 3: Time patterns of MODIS and AVHHR VIs



Appendix 5 Figure 4 shows the spatial pattern for a single year. While the ndvi_delta variable for 2001 is slightly unusual, the patterns of ndvi_delta and evi_delta are similar in all the years reported by Asher and co-authors (2001–06). For ndvi_delta VI the high values in central India do

not correspond well with what is generally thought to be the pattern of agricultural productivity in the country, as, for example, reflected in the Bhalla and Singh agricultural productivity data (see Source: Bhalla and Singh (2012).

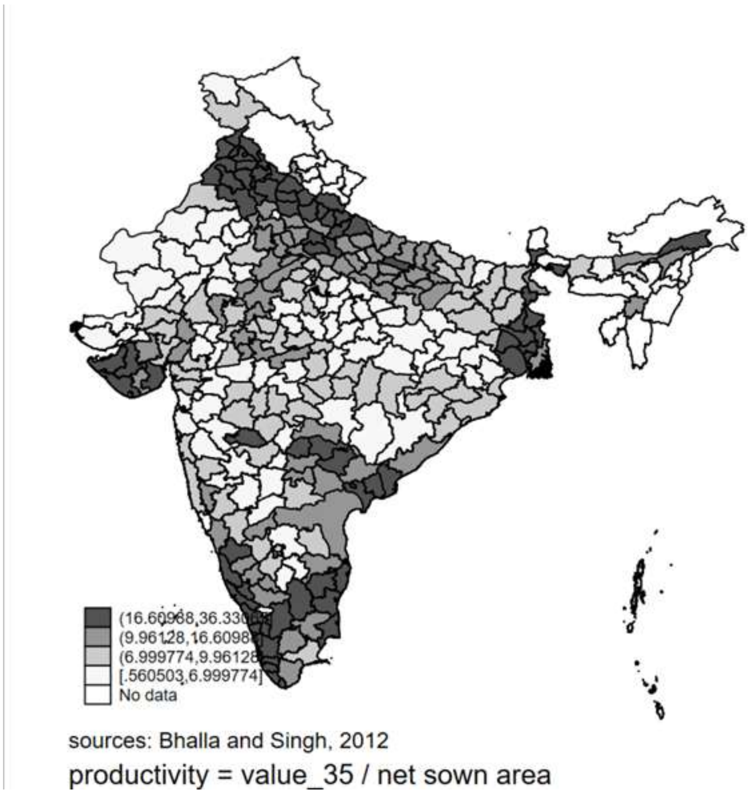
Appendix 5 Figure 4: Spatial distribution of MODIS and VHRR IV, 2001



The spatial distribution of the evi_delta VI also shows unexpectedly high values in the central belt from Orissa through Chhattisgarh, Madhya Pradesh and northern Gujarat (not shown). This may reflect high levels of 'greenness' increase between mid-May and mid-October in this area which has a high proportion of deciduous forests (which consequently are unlikely to be relevant to agricultural productivity).

Our AVHRR VI, on the other hand, does not include forest pixels, as AVHRR pixels overlying Land-Use pixels classified as forests are excluded from the calculation. Also, the AVHRR VI is likely to reflect multiple cropping as well as well as different timings of the onset and retreat of the monsoon. This variable shows higher positive VI value increases over the whole year throughout the Indo-Gangetic plains, down the east coast and in much of southern India. The visual similarity to the spatial distribution of high agricultural productivity computed by Bhalla and Singh for 2005–08 is striking (see **Appendix 5 Figure 5**), and is confirmed in **Appendix 5 Table 1**.

Appendix 5 Figure 5: Agricultural productivity, 2005–08



Source: Bhalla and Singh (2012).

Appendix 5 Table 1 mimics Asher Novosad's NDVI validation table Panel B using the Bhalla and Singh rather than SHRUG districts, and a plausibly more appropriate measure of agricultural productivity (from Bhalla and Singh, rather than District Domestic Product - DDP); it shows that with state fixed effects the AVHRR based VI performs better (in terms r^2) than the SHRUG NDVI/EVI VI used by Asher and Novosad (2020) in the 2005–08 period, where both data series are available. As with the obvious errors in geographic and agricultural variables in 'Dams' it is surprising that the limitations of the construction of the NDVI/EVI variables in Asher and Novosad, 2020, should have passed review processes of academic journals uncommented.

Appendix 5 Table 1: Agricultural productivity (Bhalla & Singh), 2005–08, and NDVI, EVI and AVHRR Vegetation Indexes (OLS)

Productivity (Bhalla), NDVI (rpj), NDVI and EVI (SHRUG)

		AVHRR NDVI		SHRUG NDVI	SHRUG EVI
	1980-83	1990-93	2005-2008	ndvi	evi
(mean) prdctvty	3.032***	2.167***	1.859***	29.260**	28.763***
	(0.229)	(0.159)	(0.144)	(9.049)	(7.341)
	[2.58,3.48]	[1.85,2.48]	[1.58,2.14]	[11.44,47.08]	[14.31,43.22]
R-squared	0.938	0.955	0.944	0.605	0.619
N	280	280	280	280	280
fe	state	state	state	state	state

se in parentheses; 95% confidence intervals in brackets
productivity = Mean sum NDVI and value_35 / net sown area
NDVI is the mean over 4 years of the sum of positive NDVI values (Tucker et al., 2005)
* p<0.05, ** p<0.01, *** p<0.001