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Climate Change and River Water Pollution: An Application to the Ganges in Kanpur[1]

by

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1

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2

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Abstract

We provide a theoretical framework to analyze how climate change influences the Ganges and how this influence affects pollution in the river caused by tanneries in Kanpur, India. We focus on two tanneries, A and B, that are situated on the same bank of the Ganges in Kanpur. Both produce leather and leather production requires the use of noxious chemicals. Tannery A is situated upstream from tannery B. Tannery $A's$ leather production depends on labor use but tannery $B's$ leather production depends on labor use, the chemical waste generated by tannery A, and the natural pollution absorbing capacity of the Ganges. In this setting, we perform four tasks. First, we construct a metric that measures the climate change induced mean reduction in the natural capacity of the Ganges to absorb pollution in the time interval $[0, t]$. Second, we use this metric and determine the equilibrium production of leather by both tanneries in the benchmark case in which there is no pollution. Third, we ascertain how the benchmark equilibrium is altered when tannery B accounts for the negative externality foisted upon it by tannery A. Finally, we study the impact on leather production and on labor use when the two tanneries merge and then discuss the policy implications stemming from our research.

Keywords: Climate Change, Ganges River, Tannery, Unitization, Water Pollution

JEL Codes: Q25, Q54

Recommendations for Resource Managers

1) Climate change worsens the impact of water pollution in the Ganges caused by tanneries in

Kanpur.

2) Climate change can mitigate and even nullify the usefulness of market based solutions to the Ganges water pollution problem.

3) Market based pollution control methods such as unitization are likely to be superior to uniform, command and control methods.

1. Introduction

There is no denying the fact that the Ganges (Ganga in Hindi) is the longest and the most noteworthy river in India. Even so, Black (2016) points out that more than a billion gallons of waste are deposited into the Ganges every day. Although the problem of waste deposition into the Ganges occurs at various points along the river, Gallagher (2014), Black (2016), and Jain and Singh (2020) note that with regard to the flow of water and pollution in the Ganges, three problems deserve particular emphasis.

The first problem is that the phenomenon of climate change is diminishing water flows in the Ganges and this factor, along with other factors, has, most likely, reduced the river's natural capacity to absorb pollutants that are deposited into it. The second problem is water pollution from the tannery industry which is centered in the city---see Figure 1---of Kanpur. The significance of

Figure 1 about here

the tannery industry in Kanpur explains why this city is sometimes referred to as India's "leather city."[5] The third problem is waste deposited into the Ganges in the city of Varanasi which is, as shown in Figure 1, located to the south-east of and approximately two hundred miles downstream from Kanpur.[6]

The problem of cleaning up pollution in the Ganges at Varanasi has recently been studied

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Go to https://mahileather.com/blogs/news/the-world-s-most-famous-leather-markets for a more detailed discussion of this point. Accessed on 16 December 2022.

6

In the next paragraph, we briefly discuss water pollution in the Ganges at Varanasi because of three reasons. First we want to emphasize the point that even though pollutants are deposited into the Ganges at a number of different points as it flows ultimately into the Bay of Bengal, the magnitude of the pollution problem is particularly severe at a *small* number of locations and Varanasi is one such location. Second, for our literature review to be complete, it is necessary to point out that even though the pollution problem in Varanasi is severe, we are *not* concentrating on this problem in the present paper because this Varanasi related Ganges pollution problem has *already been studied* by the papers mentioned in the next paragraph. Finally, by pointing out what has already been studied in the literaure, our claim that the pollution problem caused primarily by tanneries in the Kanpur area is brought onto *sharper focus*.

from a variety of perspectives by Batabyal and Beladi (2017, 2019, 2020) and by Xing and Batabyal (2019). In addition, the specific question of how best to deal with polluting tanneries in Kanpur when the water pollution they cause adversely affects small farmers has been analyzed by Batabyal *et al.* (2022). Finally and more generally, pollution in the Ganges caused by the activities of tanneries in Kanpur has been analyzed by Batabyal (2022).

To the best of our knowledge, what has *not* been studied previously in the existing literature is how the climate change phenomenon influences the Ganges and how this influence affects the upstream-downstream pollution pattern in the river caused by tanneries in the city of Kanpur in India. Given this lacuna in the literature, we generalize the analysis in Batabyal (2022) and provide the *first* theoretical analysis of how a climate change induced reduction in the Ganges river's natural capacity to absorb pollution affects the interaction between leather producing tanneries in Kanpur when this leather production also leads to pollution in the Ganges. Note that we are *not* claiming that the various tanneries in Kanpur are the sole polluters of the Ganges river. That said, we contend that the activities of tanneries are worth analyzing because tanneries collectively are the *dominant* polluters when it comes to water in the Ganges in the Kanpur area.[7]

The remainder of this paper is organized as follows: Section 2 uses a dynamic and stochastic framework to construct a metric that measures the climate change induced average[8] reduction in the natural capacity of the Ganges to absorb pollution in a particular time interval. Section 3 describes our theoretical model of pollution in the Ganges caused by tanneries in

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Go to https://www.deccanherald.com/content/454638/kanpurs-700-tanneries-major-source.html for a more detailed corroboration of this point. Accessed on 16 December 2022.

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In what follows, we use the terms *average*, *mean*, and *expected value*, interchangeably.

Kanpur.[9] There are two leather producing tanneries, A and B, that are situated on the same bank of the Ganges in Kanpur. Leather production requires the use of chemicals that are injurious to humans. Tannery A is situated upstream from tannery B. Tannery $A's$ leather production depends on labor use but tannery $B's$ leather production depends on labor use, the chemical waste generated by tannery A, and the natural pollution absorbing capacity of the Ganges.[10]

Section 4 uses the above mentioned metric and determines the equilibrium production of leather by both tanneries in the benchmark case in which there is no pollution. Section 5 shows how the benchmark equilibrium is altered when tannery B explicitly accounts for the negative externality foisted upon it by tannery A. Section 6 studies the impact on leather production and on labor use when the two tanneries merge, and then discusses the policy implications stemming from our research. Section 7 concludes and then suggests two ways in which the research delineated in this paper might be extended.

2. The Assimilative Capacity Reduction Metric

Jain and Singh (2020) rightly note that the Ganges provides a variety of ecosystem services to humans. They go on to point out that what they call the "Gangetic ecosystem" is one of the world's most vivid and complex, and that approximately 445 million people are either directly or indirectly dependent on this ecosystem. Now, the Ganges, like all rivers, has a natural capacity for

9

Our model is general in the sense that in addition to the Ganges pollution problem caused by tanneries, it can, with appropriate modifications, be used to analyze circumstances in which the interaction between two parties is characterized by the presence of a negative production externality that is unidirectional in nature.

10

The Ganges river is certainly not pollution or chemical free before it reaches tannery A in the Kanpur region. That said, since the objective of our paper is to study the river water pollution caused by tanneries---the *dominant* polluters in Kanpur---we are abstracting away from other kinds of pollution that may also be present in the Ganges. In addition, because tannery B is located *downstream* from tannery A, it is *negatively* impacted by the pollution caused by tannery A. Tannery A is not negatively impacted by the pollution caused by tannery B because this last kind of pollution would negatively impact tanneries located downstream from tannery B. Put differently, the river water pollution problem we are studying is not reciprocal but *unidirectional* in nature.

absorbing pollutants that are deposited into it.[11] However, the work of Farinosi *et al*. (2019), Chapra *et al*. (2021), and Ziogas *et al*. (2021) tells us that with the onset of climate change, over time, river water flows are expected to decline and this, along with other factors, is very likely to probabilistically *diminish* the natural capacity of a river such as the Ganges to absorb pollutants that are deposited into it.

Given these findings, we now use a *dynamic* and *stochastic* framework to construct a metric that measures the climate change induced mean reduction in the natural capacity of the Ganges to absorb pollution in the time interval $[0, t]$. To this end, suppose that because of the climate change phenomenon, water quality in the Ganges is subject to damaging shocks that occur in accordance with a homogeneous Poisson process[12] with rate $\delta > 0$. The ith shock gives rise to a *reduction* in the Ganges river's natural capacity to absorb pollution of amount $R_i > 0$. We suppose that these reduction amounts or the $R_i's, i \geq 1$, are independently and identically distributed and that they are also independent of $N(t), t \geq 0$, where $N(t)$ denotes the total number of shocks that have occurred in the time interval $[0, t]$.[13]

Even though water quality in the Ganges is subject to these climate change induced shocks, because the river's natural capacity to absorb pollution is constantly at work, we suppose that these shocks---and the attendant reductions in the river's natural pollution absorbing capacity---decrease exponentially over time. So, a shock that reduces the natural pollution absorbing capacity of the

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This natural capacity is sometimes also referred to as the assimilative capacity. See Monfared *et al*. (2017) for more details on this point.

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See Ross (1996, pp. 59-97) for a textbook exposition of the Poisson process.

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The reader should understand that the total number of shocks or N *is a function* of time t. Therefore, if t changes then $N(t)$ will typically change. In other words, $N(t)$ is *not* a constant that is independent of time t.

Ganges by an amount R at time 0 declines to an amount $Re^{-\beta t}$ at time t, where $\beta > 0$ is the parameter of the exponential distribution. Now, assuming that we can add all the shocks or the natural pollution absorbing capacity reduction amounts over time, let

$$R(t) = \sum_{i=1}^{N(t)} R_i e^{-\beta(t-S_i)} \tag{1}$$

denote the *total* reduction in the natural pollution absorbing capacity of the Ganges in the time interval $[0, t]$ and S_i is the arrival time of the ith shock.

Because the $R_i's$ are random variables, $R(t)$, which is a weighted sum of these independent random variables, is itself a *random* variable. Therefore, to use this $R(t)$ random variable in a meaningful manner in our subsequent mathematical analysis, it will be necessary to work with a measure of its central tendency. The most common and widely used measure of central tendency for a random variable is the average or mean or expected value. Therefore, in what follows, we shall be interested in working with the expected value of this $R(t)$ random variable. Let us denote this expected value by $E[R(t)]$, where $E[\cdot]$ his the expectation operator. In words, $E[R(t)]$ is the *mean* total reduction in the natural pollution absorbing capacity of the Ganges or the metric we seek.[14]

14

Note that $R(t)$ follows a stochastic process and we are interested in describing its behavior in the time interval $[0, t]$ in an analytically tractable manner. That is why we are focusing on its expected value or $E[R(t)]$. Although $R(t)$, in principle, could depend on other factors such as land use and agricultural pollutants, capturing these additional factors would make it impossible to compute a closed-form expression for $E[R(t)]$. That said, Batabyal *et al.* (2022) have recently studied the interaction between polluting tanneries and small farmers in the Kanpur region of India. Pollution caused by the tanneries can, in principle, be distinguished from other kinds of pollution because of three reasons. First, our analysis is geographically limited to a specific part of the Ganges in the Kanpur region where it is well known that the dominant polluters are tanneries. Second, the wastewater generated by tanneries contains chemicals such as chromium that are typically not generated by other polluters in the Kanpur region. Finally, effluents discharged by tanneries are identifiable by their red or brown color and by the large amount of dissolved solid wastes. Go to https://qrius.com/ganga-pollution-cases-2/ for additional details on this topic. Accessed on 16 December 2022.

Now, to determine $E[R(t)]$, we first condition on the number of shocks that have occurred in the time interval $[0,t]$. Second, we use theorem 2.3.1 in Ross (1996, p. 67) to simplify the result obtained by conditioning on $N(t)$. Finally, we use the methodology described in detail by Batabyal and Beladi (2001). The application of this methodology allows us to conclude that the expected pollution absorption capacity reduction is given by[15]

$$E[R(t)] = \frac{\delta E[R](1-e^{-\beta t})}{\beta}. \quad (2)$$

Equation (2) gives us an analytic or closed-form expression for the mean total reduction in the Ganges river's natural pollution absorbing capacity in the time interval $[0,t]$. Two points are now worth emphasizing. First, our analysis in this second section of the paper is both *dynamic* and *stochastic* in the sense that the metric we have computed in equation (2) is the result of probabilistic natural events that have occurred over time and specifically in the interval $[0,t]$. Second, the remainder of the analysis we undertake in this paper is *static* in the sense that it is concerned with economic activities that occur at a point in time and specifically at time t, which is also the right endpoint of the time interval $[0,t]$. With this dynamic and stochastic versus static distinction out of the way, we are now in a position to delineate our model of water pollution in the Ganges river that is caused by tanneries in the city of Kanpur in India.

3. The Model of Water Pollution

Consider two tanneries, denoted by A and B, that are situated on the same bank of the

15 Readers interested in the specific details of this computation process ought to consult the paper by Batabyal and Beladi (2001).

Ganges in Jajmau, an industrial suburb of Kanpur. It makes sense to focus on Jajmau because a large number of the tanneries in Kanpur are located in this suburb.[16] The two tanneries under study produce leather and the production of leather requires the use of chemicals that are toxic to humans. Tannery A is situated upstream from tannery B. Observe that because tannery A (B) is located upstream (downstream) from tannery B (A), there is a clear *spatial* aspect to the analysis that we are undertaking in this paper. In addition, given our interest in studying pollution in the Ganges, the relevant factor that we are emphasizing is the transmission of pollutants *not* over land but through water in the river.[17]

Tannery $A's$ production function for leather is given by

$$X = \Gamma L_A^{1/2}, \tag{3}$$

where Γ is a positive coefficient, L_A is the amount of labor used to produce leather, and X is the amount of leather produced.[18] Tannery B has a similar production function but the leather it produces can be affected by both the chemical waste generated by tannery A and the Ganges river's natural capacity for absorbing pollutants deposited into it. Let us denote this natural absorptive capacity at time t by X_0. Then, it follows that this natural capacity ought to be

16 Go to https://en.wikipedia.org/wiki/Jajmau for additional details on Jajmau. Accessed on 16 December 2022.

17 In an alternate interpretation of our model, tanneries A and B would represent groups of tanneries where the A group consists of tanneries that are all located upstream of the B group. In this way of viewing our model, the group B tanneries would be negatively impacted by the cumulative pollutants (such as chemical waste) deposited into the Ganges by all the different group A tanneries.

18 We use the square root production function because of two reasons. First, the use of this kind of production function allows us to obtain concrete and interpretable results with our mathematical modeling. Second, there is a precedent in the existing literature for using this kind of production function. Recently, Batabyal (2022) has also used this kind of function to analyze aspects of water pollution in the Ganges.

functionally related to the mean total reduction in the Ganges river's natural pollution absorbing capacity in the time interval $[0, t]$ given in equation (2). Let us express this functional relationship by writing

$$X_0 = f\{E[R(t)]\}, \tag{4}$$

where $f'\{\cdot\} < 0$. Note that our mathematical description in equation (4) of the relationship between X_0 and $E[R(t)]$ and the point that the function $f\{\cdot\}$ is decreasing in the argument $E[R(t)]$ are entirely consistent with our evidence based---see Farinosi *et al*. (2019), Chapra *et al*. (2021), and Ziogas *et al*. (2021)---previous discussion of these matters in the first paragraph of section 2. In addition and in words, what equation (4) is telling us is intuitively plausible: If the mean total reduction in the natural pollution absorbing capacity up to time t increases then the Ganges river's *actual* natural capacity for absorbing pollution at time t decreases.

With the above functional relationship in place, we can now write tannery $B's$ production function for leather as

$$Y = \begin{cases} \Gamma L_B^{1/2}(X - X_0)^{-\alpha}, X > X_0 \\ \Gamma L_B^{1/2}, X \leq X_0 \end{cases}, \tag{5}$$

where L_B is the amount of labor used to produce leather, Y is the amount of leather produced, X_0 is given by equation (4), and $\alpha \geq 0$ is a parameter whose meaning is discussed in greater detail in sections 4 and 5 below.[19] To understand the top line on the right-hand-side (RHS) of the production function in equation (5), note the following three-part line of reasoning: First, recall that tannery B is located *downstream* from tannery A. This means that tannery $B's$ ability to produce leather *depends* in part on the chemical waste generated as a byproduct of the production of leather by tannery A. Second, if tannery A produces an amount of leather so that the attendant chemical waste is *larger* than the Ganges river's natural pollution absorptive capacity (this happens when $X > X_0$) then this fact *negatively* affects the amount of leather that tannery B can produce. We model this aspect of tannery $B's$ leather production by multiplying the term $\Gamma L_B^{1/2}$ with the term $(X - X_0)^{-\alpha}$. In this regard, to emphasize the pollution created by tannery A by way of its chemical waste deposition into the Ganges and to obtain sensible mathematical results in sections 4 and 5 below, we assume that $(X - X_0) > 1$. Finally, we reiterate that unlike tannery B, tannery A faces no similar negative impact on its ability to produce leather because it is located *upstream* from tannery B on the Ganges river.

The price of a unit of leather is given by p and the wage paid per unit of labor is w. It is understood that both the tanneries under consideration are profit maximizers.[20] With this

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19

Two points about the production functions described by equations (3) and (5) deserve additional commentary. First, the positive coefficient Γ in the two production functions is identical in the interest of analytical tractability. If we used different coefficients then some of our subsequent results would *not* be clear-cut and we would have to impose additional restrictions on the model to obtain interpretable results. Second, we use the exponent $1/2$ in these same two production functions because, as the midpoint of the interval $(0, 1)$, this is the most straightforward---and least biased---way of capturing the notion of decreasing returns to scale in production.

20

To maintain our focus on water pollution in the Ganges caused by tanneries in the presence of climate change, we have modeled what we believe are the *two most important* inputs used by tanneries, namely, labor and chemicals. This does *not* mean that no other inputs are used by tanneries. In this regard, we acknowledge that water is also an input used by tanneries. Even so, we emphasize that in the context of tanneries in Kanpur, water scarcity has rarely been mentioned as a problem. That is why we do not focus on water use in our paper. Similarly, we acknowledge that the labor market in the Kanpur region could have an impact on the wage rate w that we work with. That said, the reader should understand that an analysis of either a potential tradeoff between "water quantity and quality" or how the wage rate specifically impacts river water pollution is beyond the scope of this paper.

description of the basic model of water pollution in place, we are now in a position to solve for the equilibrium production of leather by tanneries A and B in the benchmark case in which there is no pollution to contend with.

4. The Benchmark Case

The profit function of tannery A or Π_A can be written as

$$\Pi_A = pX - wL_A = p\Gamma L_A^{1/2} - wL_A. \tag{6}$$

The first-order necessary condition for an optimum is[21]

$$\frac{d\Pi_A}{dL_A} = (1/2)p\Gamma L_A^{-1/2} - w = 0. \tag{7}$$

Manipulating equation (7), the optimal amount of labor that ought to be employed by tannery A is given by

$$L_A^* = \left\{\frac{(1/2)p\Gamma}{w}\right\}^2. \tag{8}$$

Substituing L_A^* from equation (8) into the production function given by equation (3), the optimal amount of leather produced by tannery A is

21

The second-order sufficient condition is satisfied.

$$X^* = \frac{(1/2)p\Gamma^2}{w}. \quad (9)$$

In words, to maximize profit, tannery A ought to hire L_A^* units of labor to produce X^* units of leather.

The profit function of tannery B is

$$\Pi_B = pY - wL_B = \begin{cases} p\Gamma L_B^{1/2}(X - X_0)^{-\alpha} - wL_B, X > X_0 \\ p\Gamma L_B^{1/2} - wL_B, X \leq X_0 \end{cases}. \quad (10)$$

The first-order necessary conditions for an optimum are[22]

$$\frac{d\Pi_B}{dL_B} = \begin{cases} (1/2)p\Gamma L_B^{-1/2}(X - X_0)^{-\alpha} - w = 0, X > X_0 \\ (1/2)p\Gamma L_B^{-1/2} - w = 0, X \leq X_0 \end{cases}. \quad (11)$$

Manipulating the above first-order necessary conditions and then solving for the optimal values of the two choice variables of interest, i.e., of L_B^* and Y^*, we get

$$L_B^* = \begin{cases} \left[\frac{(1/2)p\Gamma}{w}(X - X_0)^{-\alpha}\right]^2, X > X_0 \\ \left[\frac{(1/2)p\Gamma}{w}\right]^2, X \leq X_0 \end{cases}. \quad (12)$$

22 The second-order sufficient conditions are satisfied.

and

$$Y^* = \begin{cases} \frac{(1/2)p\Gamma^2}{w}(X - X_0)^{-2\alpha}, X > X_0 \\ \frac{(1/2)p\Gamma^2}{w}, X \leq X_0 \end{cases}. \tag{13}$$

So, if tannery B would like to maximize its profit then it ought to hire an amount of labor indicated by equation (12) and then use this labor to produce the quantity of leather given by equation (13).

We are now in a position to answer the question about optimal leather production when there is *no* pollution to contend with. If tannery $A's$ production of leather causes no pollution in the Ganges then this tannery clearly imposes no costs on tannery B. In other words, tannery $A's$ activities do *not* give rise to an external diseconomy for tannery B. Note that in our model, the strength of the external diseconomy that we have just referred to is captured by the parameter α. That said, if there is no pollution to contend with and therefore no negative externality then we can set the value of $\alpha = 0$. Doing this in equation (13) and then using equation (9), we see that the optimal amount of leather production is

$$X^* = Y^* = \frac{(1/2)p\Gamma^2}{w}. \tag{14}$$

Let us conclude our analysis of the benchmark case with two observations. First, when there is no pollution to contend with, there is no negative externality and hence the fact that tannery B is situated downstream from tannery A does *not* handicap it in any way as far as the production of leather is concerned. Second, from equations (4) and (5), it is clear that the way in which we have modeled the impact of climate change, this phenomenon affects labor hire and therefore leather production only through the $(X - X_0)^{-\alpha}$ term. Put differently, pollution in the Ganges and the ability of this river to absorb this pollution go hand-in-hand. Therefore, when there is no pollution, *ipso facto*, there is also *no* climate change related effect on leather production by the two tanneries under study. This feature of our analysis *changes* when tannery A pollutes and tannery B explicitly accounts for the negative externality inflicted upon it by tannery A.[23] As such, we now analyze the nature of this change in the following section.

5. Accounting for the Negative Externality

We begin by pointing out that the pollution parameter α and the Ganges river's natural capacity to absorb pollution or X_0 do *not* alter the profit maximizing amount of leather produced by tannery A. Therefore, consistent with equation (9), once again, we get $X^* = (1/2)p\Gamma^2/w$. That said, because the pollution parameter α is now positive, the optimality conditions governing labor use (L_B^*) and leather production (Y^*) by tannery B are given in the top line of the expressions on the RHSs of equations (12) and (13).

Now, using equations (8) and (12), we can compare optimal labor use by tanneries A and B when the negative externality imposed by tannery A on tannery B adversely impacts the latter's ability to produce leather. This involves comparing the expressions $L_A^* = \{(1/2)p\Gamma/w\}^2$ and $L_B^* = [\{(1/2)p\Gamma/w\}(X - X_0)^{-\alpha}]^2$. Because the term $(X - X_0) > 1$, manipulating these two expressions algebraically, we obtain $L_A^* > L_B^*$. Next, let us compare the optimal production of

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We acknowledge that climate change can give rise to extreme events, that it can be modeled in different ways, and that it brings uncertainty into the decision-making of economic agents. We *have* explicitly accounted for this uncertainty in our section 2 analysis leading up to the computation of the expectation $E[R(t)]$. In addition, since this expectation impacts the ability of tannery B to produce leather, we *are* also accounting for the fact that the climate change phenomenon affects decision-making by individual firms (tanneries). That said, our objective in this paper is *not* to study the time preferences of tanneries and that of a social planner and therefore an analysis of this last point is beyond the scope of our paper.

leather by these two tanneries. We now use equations (9) and (13) to compare the outputs of leather by the two tanneries when pollution matters, i.e., when $\alpha > 0$. Specifically, we compare $X^* = (1/2)p\Gamma^2/w$ and $Y^* = [\{(1/2)p\Gamma^2/w\}(X - X_0)^{-2\alpha}]$. Once again, because $(X - X_0) > 1$, algebraically manipulating the preceding two expressions, we get $X^* > Y^*$.

The results obtained in the previous paragraph tell us that when $\alpha > 0$, there is an external diseconomy imposed by tannery A on the leather production ability of tannery B. Specifically, the magnitude of the parameter α measures the strength of this external diseconomy. *Ceteris paribus*, a higher value of α tells us that the external diseconomy is stronger and therefore it has a greater effect on leather production by tannery B. Tannery A disregards this negative externality and hence it hires *extra* labor and produces *more* leather than is socially optimal.

Let us now analyze how the phenomenon of climate change influences the hiring of labor and the production of leather by tannery B when it accounts for the negative externality imposed on it by tannery A. Recall from section 2 that the mean total reduction in the natural capacity of the Ganges to absorb pollution is given by equation (2). Now, consider a thought experiment in which we proxy the severity of the climate change problem with the rate of the Poisson process or $\delta > 0$. This means that, *ceteris paribus*, when climate change becomes a more serious problem the rate δ goes up. Now, inspecting equations (2) and (4), we observe that $\delta \uparrow \ \Rightarrow E[R(t)] \uparrow \ \Rightarrow \ X_0 \downarrow$. This means that compared to its magnitude before our thought experiment, i.e., before δ went up, the term $(X - X_0)$ is now larger and hence optimal labor use and leather production by tannery B are now lower---see equations (12) and (13)---than what they previously were. In other words, as the severity of the climate change problem increases, the equilibrium amount of leather produced by tannery B *declines*. Our final task in this paper is to analyze what happens to labor use and to leather production when the two tanneries merge.[24]

6. Unitization

The profit function of the newly merged or unitized tannery is

$$\Pi = \Pi_A + \Pi_B = p(X+Y) - w(L_A + L_B). \tag{15}$$

Making the appropriate substitutions and then simplifying the resulting expression, the above profit function can be written as

$$\Pi = -w(L_A + L_B) + \begin{cases} p\Gamma[L_A^{1/2} + L_B^{1/2}\left(\Gamma L_A^{1/2} - X_0\right)^{-\alpha}], L_A > \left(\frac{X_0}{\Gamma}\right)^2 \\ p\Gamma\left[L_A^{1/2} + L_B^{1/2}\right], L_A \leq \left(\frac{X_0}{\Gamma}\right)^2 \end{cases}. \tag{16}$$

The two inequalities in the top and in the bottom lines on the RHS of equation (16) follow because $X \gtreqless X_0$ implies from equation (3) that $\Gamma L_A^{1/2} \gtreqless X_0$ and this last expression, in turn, tells us that $L_A \gtreqless (X_0/\Gamma)^2$.

The first-order necessary conditions for an optimum are[25]

$$\frac{\partial \Pi}{\partial L_A} = -w + \begin{cases} (1/2)p\Gamma L_A^{-1/2}\left\{1 - \alpha\Gamma L_B^{1/2}\left(\Gamma L_A^{1/2} - X_0\right)^{-\alpha-1}\right\}, L_A > \left(\frac{X_0}{\Gamma}\right)^2 \\ (1/2)p\Gamma L_A^{-1/2}, L_A \leq \left(\frac{X_0}{\Gamma}\right)^2 \end{cases}, \tag{17}$$

24

This process is sometimes also referred to as unitization in the natural resource and environmental economics literature. See Hartwick and Olewiler (1998) for a textbook exposition of unitization.

25

The second-order sufficient conditions are satisfied.

and

$$\frac{\partial \Pi}{\partial L_B} = -w + \begin{cases} (1/2)p\Gamma L_B^{-1/2}\left(\Gamma L_A^{1/2} - X_0\right)^{-\alpha}, L_A > \left(\frac{X_0}{\Gamma}\right)^2 \\ (1/2)p\Gamma L_B^{-1/2}, L_A \leq \left(\frac{X_0}{\Gamma}\right)^2 \end{cases}. \quad (18)$$

Using equations (17) and (18), we can determine the equilibrium labor demand functions. Specifically, after algebraically manipulating these two equations, we infer the equilibrium demand for labor. In our case, the two relevant demand functions for L_A^e and L_B^e (the superscript *e* denotes equilibrium) are given implicitly by

$$L_A^e = \begin{cases} \left[\frac{(1/2)p\Gamma}{w}\right]^2 \left[1 - \alpha\Gamma L_B^{1/2}\{\Gamma(L_A^e)^{1/2} - X_0\}^{-\alpha-1}\right]^2, L_A^e > \left(\frac{X_0}{\Gamma}\right)^2 \\ \left[\frac{(1/2)p\Gamma}{w}\right]^2, \quad L_A^e \leq \left(\frac{X_0}{\Gamma}\right)^2 \end{cases}, \quad (19)$$

and

$$L_B^e = \begin{cases} \left[\frac{(1/2)p\Gamma}{w}\right]^2 \left\{\Gamma(L_A^e)^{1/2} - X_0\right\}^{-2\alpha}, L_A^e > \left(\frac{X_0}{\Gamma}\right)^2 \\ \left[\frac{(1/2)p\Gamma}{w}\right]^2, L_A^e \leq \left(\frac{X_0}{\Gamma}\right)^2 \end{cases}. \quad (20)$$

Let us now concentrate on the equilibrium labor demand functions in equations (19) and (20) and the corresponding expressions for L_A^* and L_B^* in equations (8) and (12). There are two tasks that we wish to accomplish now. The first is to show that $L_A^* > L_A^e$. To this end, we compare

L_A^* from equation (8) with L_A^e from equation (19) when the inequality $L_A^e > (X_0/\Gamma)^2$ holds. In other words, we are comparing the magnitude of $L_A^* = \{(1/2)p\Gamma/w\}^2$ with that of $L_A^e = \{(1/2)p\Gamma/w\}^2\left[1 - \alpha\Gamma L_B^{1/2}\{\Gamma(L_A^e)^{1/2} - X_0\}^{-\alpha-1}\right]^2$. Manipulating these two expressions algebraically, we see that showing $L_A^* > L_A^e$ is equivalent to showing that $0 > -\left[\alpha\Gamma L_B^{1/2}/\left\{\Gamma(L_A^e)^{1/2} - X_0\right\}^{\alpha+1}\right]$. This last inequality clearly holds because the numerator and the denominator of the ratio on the RHS of the above inequality are both positive. Therefore, we conclude that L_A^* is indeed *bigger* than L_A^e.

Our second task is to demonstrate that $L_B^e > L_B^*$. To this end, we compare L_B^* when $X > X_0$ from equation (12) with L_B^e when $L_A^e > (X_0/\Gamma)^2$ from equation (20). Put differently, we are comparing the magnitude of $L_B^e = \{(1/2)p\Gamma/w\}^2\left\{\Gamma(L_A^e)^{1/2} - X_0\right\}^{-2\alpha}$ with that of $L_B^* = [\{(1/2)p\Gamma/w\}(X - X_0)^{-\alpha}]^2$. As in the preceding paragraph, a series of algebraic manipulations show that demonstrating $L_B^e > L_B^*$ is equivalent to demonstrating $\left\{\Gamma(L_A^e)^{1/2} - X_0\right\}^{-1} > \left(\Gamma(L_A^*)^{1/2} - X_0\right)^{-1}$. This last inequality holds because we have already shown that $L_A^* > L_A^e$.[26]

The results contained in the previous two paragraphs tell us that the merged or unitized tannery employs *less* labor than the original tannery A and *more* labor than the original tannery B. This means that the newly merged tannery has a clear incentive to reallocate labor from the original tannery A to the original tannery B. This result arises because the newly unitized tannery effectively internalizes the negative externality and, therefore, it lowers the labor input and the

26 The reader can verify that because of the *comparative* nature of our analysis in this section, the two basic results $L_A^* > L_A^e$ and $L_B^e > L_B^*$ that we have just obtained do *not* depend on writing the equilibrium labor demand function in equation (19) explicitly. Also, the manner in which we have written this labor demand function in equation (19) is necessitated by the fact that it is *not* possible to write the top line of equation (19) explicitly. In this regard, we would like to point out that to the best of our knowledge and as noted in section 1, the present paper is the *first* in the literature to theoretically demonstrate how the climate change phenomenon affects the nature of resource utilization in the context of river water pollution in the Ganges.

output of leather from the original tannery A. This lowering makes it profitable to raise the labor input and the output of leather in the previous tannery B.

The work of Chitnis (2017) and Batabyal (2022) tells us that even though a number of industries are responsible for pollution in the Ganges, tanneries in Kanpur are among the worst offenders. Therefore, there is no doubt that tanneries deserve to be looked at carefully by regulators. According to Sahu (2019), there are more than 400 tanneries in Kanpur and many of these tanneries are responsible for water pollution in the Ganges. As such, a straightforward policy implication of our analysis is that a number of these polluting tanneries ought to be merged into larger entities. Such an action is likely to ameliorate water quality in the Ganges.

The polluting tanneries in the Jajmau region do not have a "property right" to pollute the water in the Ganges.[27] This notwithstanding, the reader may be wondering whether Coasian bargaining between tanneries A and B will lead to the socially desirable outcome. Although Coasian bargaining is a theoretically appealing solution to the Ganges water pollution problem, this kind of bargaining is most likely to be successful when---see Hartwick and Olewiler (1998, pp. 194-199) or Hindriks and Myles (2013, pp. 242-247)---the transaction costs associated with such bargaining are low and ideally zero. However, even though we have worked with two stylized tanneries to illustrate salient aspects of the interaction between the climate change phenomenon and river water pollution, in reality, there are *more than* 400 tanneries in the Kanpur region and therefore the costs associated with bargaining between such a large number of firms is unlikely to be low and certainly not zero. In other words, it is not clear at all that such bargaining approaches

27 Go to https://www.thehindu.com/news/national/other-states/nowhere-to-hide/article61537391.ece for a more detailed corroboration of this claim. Accessed on 16 December 2022.

will help attenuate the severity of the Ganges water pollution problem.

Let us now study how climate change affects the hiring of labor and the production of leather by the merged tannery. As in section 5, we proxy the severity of the climate change problem with the rate of the homogeneous Poisson process or $\delta > 0$. As such, *ceteris paribus*, when climate change becomes a more serious problem, the parameter δ increases in magnitude. Now, reviewing equations (2) and (4), we see that $\delta \uparrow \Rightarrow E[R(t)] \uparrow \Rightarrow X_0 \downarrow$. This means that compared to its magnitude before δ went up, the term $(X - X_0)$ and therefore the term $\{\Gamma(L_A^e)^{1/2} - X_0\}$ are now *larger*. Using this last result in equation (19), we see that because $\left\{\Gamma(L_A^e)^{1/2} - X_0\right\} \uparrow \Rightarrow 1/\{\Gamma(L_A^e)^{1/2} - X_0\}^{(\alpha+1)} \downarrow$, it follows that $L_A^e \uparrow$. Similarly, using the result $\left\{\Gamma(L_A^e)^{1/2} - X_0\right\} \uparrow$ in equation (20), we infer that $1/\left\{\Gamma(L_A^e)^{1/2} - X_0\right\}^{2\alpha} \downarrow \Rightarrow L_B^e \downarrow$. In words, the impact of a progressively more damaging kind of climate change on the merged tannery is to *increase* labor use by the original tannery A and to *decrease* labor use by the original tannery B.

Now recall that the merged tannery employs *less* labor than the original tannery A and *more* labor than the original tannery B. That said, the findings obtained in the preceding paragraph run *counter* to those stated for unitization because the impact of climate change is to increase (decrease) labor use by the original tannery A (B). The salient policy conclusion emanating from this analysis is that accounting for climate change can *diminish* the benefits of unitization and, in principle, it can even nullify these benefits if the climate change induced labor use increase (decrease) by the original tannery A (B) offsets the decrease (increase) in labor use by the original tannery A (B) that unitization calls for. More generally, our analysis suggests that in the presence of climate change, the usefulness of market based instruments in mitigating the problem of water pollution in the Ganges is likely to be more limited than has been recognized previously in the literature. This completes our theoretical analysis of how climate change affects the Ganges and water pollution by tanneries in Kanpur.

6. Conclusions

In this paper, we examined how the climate change phenomenon impacted the Ganges and how this impact affected pollution in the river caused by tanneries in the city of Kanpur in India (see Figure 1). We focused on two stylized tanneries, A and B, that were situated on the same bank of the Ganges in Kanpur. Both produced leather and leather production required the use of chemicals that were deleterious to humans. Tannery A was situated upstream from tannery B. Tannery $A's$ leather production depended only on labor use but tannery $B's$ leather production depended on labor use, the chemical waste generated by tannery A, and the natural pollution absorbing capacity of the Ganges. In this setting, we performed four tasks. First, we constructed a metric that measured the climate change induced average reduction in the natural capacity of the Ganges to absorb pollution in a given time period. Second, we used this metric and determined the equilibrium production of leather by both tanneries in the benchmark case in which there was no pollution. Third, we ascertained how the benchmark equilibrium was altered when tannery B accounted for the negative externality imposed on it by tannery A. Finally, we studied the impact on leather production and on labor use when the two tanneries merged and then we discussed the policy implications stemming from our research.

Here are two suggestions for extending the research described in this paper. First, it would be useful to analyze the interaction between tanneries A and B when either or both tanneries, when merged, take mitigation measures to reduce the adverse impacts of climate change. Second, it would also be helpful to study the outcome of a process in which a suitable administrative authority in the state of Uttar Pradesh---where Kanpur is located---is able to dispense with costly regulations and to use a market mechanism to merge a number of the existing tanneries in Kanpur. Studies of the prevention of water pollution caused by tanneries in Kanpur in the presence of ongoing climate change that incorporate these aspects of the problem into the analysis will provide additional perspectives on the ways in which tanneries can continue to exist as an industry and, at the same time, the environmental harm done to the Ganges and to humans living in the vicinity of these tanneries is alleviated to the extent possible.

Figure 1: Flow of the Ganges and the Location of Kanpur

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