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by

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1. Introduction

The Ganges is the longest river in India and it occupies a central place in Hinduism. Hindus consider the Ganges to be sacred and millions of them visit the holy city of Varanasi to, *inter alia*, bathe in the river. Varanasi is important not only for "religious tourism" but also for tourism more generally because it is one of the oldest cities in the world.

Unfortunately, pollutants are now routinely deposited into the Ganges. In Varanasi, one can find animal carcasses, partially cremated corpses, and the material offerings of Hindu devotees in the river. Given this insalubrious state of the river, questions are currently being asked about the sustainability of tourism in Varanasi.

The clean-up of the Ganges now appears to have a champion in the Indian Prime Minister Narendra Modi. Modi contested the 2014 election from Varanasi and he has promised to convert Varanasi into a vibrant city for tourists by launching a major campaign to clean the Ganges. Despite the salience of this campaign from environmental and touristic standpoints, the extant literature contains *no* theoretical studies of the clean-up of the Ganges and its connection to tourism. Hence, we use a simple model and provide the *first* stochastic analysis of the Ganges clean-up process and the attraction of tourists to Varanasi.

2. The Theoretical Framework

Consider a designated portion of the Ganges in Varanasi. The objective of a city authority (CA) is to clean-up this portion. To model the *random* discharge of pollutants such as raw sewage into this designated portion of the Ganges, we suppose that these discharges occur in accordance with a stationary Poisson process (H.C. Tijms, *A First Course in Stochastic Models*, 2003, pp. 1-32) with rate or parameter $\alpha > 0$. The successive amounts of pollutants deposited into the Ganges are independent and identically distributed random variables with finite first and second moments $\beta_1 > 0$ and $\beta_2 > 0$. The CA cleans the relevant portion of the Ganges at a constant rate $\zeta > 0$.

We posit that the sustainability of the tourism industry in Varanasi (S) is an increasing function $f\{\cdot\}$ of the cleanliness of the Ganges and some sites along the Ganges (C). In symbols, $S = f\{C\}$. Cleanliness (C) is an increasing function $g(\cdot)$ of the cleanup rate (ζ) and hence $C = g(\zeta)$. Therefore, $S = f\{g(\zeta)\}$ and the sustainability of the tourism industry is itself an *increasing* function of the cleanup rate. We now ascertain a closed-form expression for the long run average waste in the designated portion of the Ganges.

We begin by providing an interesting *queuing-theoretic* interpretation of our model. The Poisson process driven discharges of pollutants into the Ganges are like the Poisson arrivals of customers to a service station. Second, our CA corresponds to the server in a queuing model. Finally, the CA's clean-up times are generally distributed. Therefore, our Ganges clean-up model is related to the well-known $\langle M|G|1\rangle$ queuing model (Tijms, 2003, pp. 58-65).

Let $P(t)$ denote the time t quantity of pollutants in the designated portion of the Ganges. To compute the long run average waste metric, we use two mathematical results from the existing literature on stochastic processes (Tijms 2003). The first result is the "Poisson arrivals see time averages" or PASTA property (Tijms 2003, pp. 53-58). Intuitively, this result tells us that in the long run, the *rate* at which arrivals find a stochastic system in a particular state is equal to the *proportion* of arrivals that find this system in the same state.

We now apply this PASTA property to our model. In doing so, we shall use existing knowledge about the long run distribution of the delay in queue for an arriving customer for the $\langle M|G|1\rangle$ model (Tijms 2003, pp. 58-62) because our model is related to this queuing model. Our application tells us that the long run distribution of $P(t)$ is identical to the long run distribution of the delay in queue for an arriving customer when the service provided to customers in the queue is in order of arrival.

The second mathematical result we use is the Pollaczek-Khintchine formula (Tijms 2003, pp. 58-60). For the $\langle M|G|1\rangle$ queuing model, this formula gives us a closed-form expression for the *average* amount of time a customer spends waiting in queue. Note that in our Ganges cleanup model, we would like to obtain a closed-form expression for the *average* amount of waste in the relevant portion of the Ganges. Therefore, applying the formula, the long run average waste in the Ganges is

$$Long\ run\ average\ amount\ of\ waste = \frac{\alpha\beta_2/\zeta^2}{1-\alpha\beta_1/\zeta}. \qquad (1)$$

Inspecting (1), because the average waste metric must be non-negative, when $\alpha,\ \beta_1,$ and β_2 increase, this metric rises. These three constants have everything to do with the discharge of pollutants into the Ganges. Even so, it is unlikely that our CA will be able to control any of these constants. What our CA can control is ζ or the rate at which it cleans up pollutants.

The CA's objective is to choose ζ to minimize the long run average waste in (1). Our CA solves

$$Min_{\{\zeta\}}[\frac{\alpha\beta_2/\zeta^2}{1-\alpha\beta_1/\zeta}]. \qquad (2)$$

Differentiating (2) with respect to ζ and then simplifying, the necessary optimality condition is

$\zeta^* = \alpha\beta_1/2.$ If our CA chooses the cleaning rate in this manner then the long run average waste in the Ganges will be minimal.

From section 1, the sustainability of the tourism industry in Varanasi is an increasing function of the cleanup rate. In symbols, we have $S = f\{g(\zeta)\}$. Therefore, by selecting the cleaning rate optimally (ζ^*), the CA will be cleaning the Ganges optimally and this implies that we'll have the optimal level of sustainability or $S^* = f\{g(\zeta^*)\}$ for the Varanasi tourism industry.

3. Extensions

One can generalize this analysis by studying the maximization of social welfare in Varansi when this welfare depends on a CA's actions and on the actions of city residents and tourists. Second, it would be helpful to analyze the role that temporal regulations on alternate touristic activities have on Varanasi's ability to sustainably utilize the services provided by the Ganges.