



# District-wise estimation of Basic reproduction number ( $R_0$ ) for COVID-19 in India in the initial phase

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**Abstract** SARS-CoV-2 or COVID-19 was introduced into India by multiple sources generating local clusters and leading to the nationwide spread. A retrospective study has been conducted on the epidemiological features and spatial spread of COVID-19 in India during February 2020–March 2021. For each district, the cumulative number of confirmed COVID-19 cases were fitted to exponential growth model for the initial phase of the outbreak (the first 7–15 days). From the estimated growth rate, epidemiological parameters like the Basic reproduction number ( $R_0$ ) and epidemic doubling time ( $\tau$ ) were determined. Using Q-GIS software, we have generated the all India distribution maps for  $R_0$  and  $\tau$ . COVID-19 spread rapidly covering majority of the districts of India between March and June 2020. As on 1st March 2021, a total of 715 out of 717 districts have been affected. The  $R_0$  range is at par with the global average. A few districts, where outbreaks were caused by migrant workers coming home, intense transmission was recorded  $R_0 > 7$ . We also found that the spread of COVID-19 was not uniform across the different districts of India. The methodology developed in the study can be used by researchers and public health professionals to analyze and study epidemics in future.

**Keywords** COVID-19 · India · Basic reproduction number · Doubling time · Districts

## 1 Introduction

The novel coronavirus or COVID-19 [1] has created a pandemic of an unprecedented proportion as it emerged from Wuhan, China and rapidly spread worldwide. The rapid spread of the pandemic and the high burden of disease has strained the health care systems across the world and caused severe economic distress [2, 3]. In India, as the pandemic has completed one year in March 2021 we retrospect on the spread of the COVID-19 across the districts of the country. There had been a few papers from China that described the epidemiological aspects of the outbreaks. Attempts have been made to estimate the epidemiological parameters such as Basic reproduction number ( $R_0$ ), which are markers for intensity of the spread of COVID-19 [4–9].

Basic reproduction number,  $R_0$ , is defined as the measure of the number of secondary infections generated by an infected individual when introduced into a fully susceptible population [10].  $R_0$  is used to measure the transmission potential for any disease. It is also used as a parameter to estimate the severity of viral epidemics [11, 12]. If  $R_0 < 1$ , then on an average an infected individual spreads the pathogen to less than one susceptible individual and the outbreak dies out after a few cases in the population. If  $R_0 > 1$ , then the outbreak progresses into an epidemic with the number of infected individuals increasing exponentially [10–12]. Different methods have been employed to estimate the  $R_0$  for COVID19 in various countries giving rise to ranges of values [1, 13–17].

Even for China, the estimated values of  $R_0$  in Wuhan prior to lockdown was 6.6 [18]. Studies on mathematical modelling from India are sparse. Mandal et al., 2020 [19] had projected various scenarios indicating the prudent public health strategies for control of COVID-19 in India. They have projected  $R_0 = 4.0$  considering inter-country

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spread following introduction by international travelers. However, at the time of their analyses, no cases had been reported from India. Hence, their models relied on parameters from other countries. Taking into account the vastness of India including its geographical and climatic diversity, demographic diversity and varied socio-cultural practices, it is hypothesized that considerable variation may be expected in the transmission potential of COVID-19 in the different parts of the country. To the best of our knowledge no comprehensive report exist to describe this. This necessities research on the estimation of epidemiological parameters at regional levels.

In the present study, we have estimated the basic reproduction number ( $R_0$ ) and doubling time for COVID-19 for the all districts of India in the respective initial phase (beginning of cases in each district).

## 2 Materials and methods

### 2.1 Epidemiological data

District-wise data of daily confirmed cases of COVID-19 were obtained from <https://howindialives.com/gram/coronadistricts/> and <https://www.covid19india.org/>. We set-up our own updated dataset and cured the same for mathematical analyses and GIS applications. District-wise time series datasets were prepared.

### 2.2 Mathematical formulation

Key epidemiological parameters like the growth rate, basic reproduction number and doubling time of outbreaks in each district were estimated for the initial phase. For each district dataset, a time-series for the cumulative confirmed cases was prepared. The growth of cumulative number of confirmed COVID-19 cases ( $y$ ) with time ( $t$ ) was considered exponential and studied graphically [10–12]. The growth rate ( $r$ ) of the outbreak was calculated by fitting the cumulative number of cases to the equation for exponential growth:

$$y = y_0 e^{rt} \quad (1)$$

where  $y_0$  is the initial number of cases. The best-fit solution was considered for each district.

The basic reproduction number ( $R_0$ ) was estimated as:

$$R_0 = \left(1 + \frac{r}{k}\right) \left(1 + \frac{r}{\theta}\right) \quad (2)$$

where  $1/\theta$  is the mean onset-to isolation period,  $1/k$  is the mean latent period (incubation period) and  $r$  is the intrinsic growth rate of the epidemic (Eq. 1). By “Onset-to-isolation” we mean the time period between onset of symptoms

in an individual and the start of hospitalization with isolation (as practiced in India). It is assumed that during this period, the person is freely moving around and interacting with members of the population and spreading infection [11].

The doubling time for the epidemic was estimated as

$$\tau = (\ln 2)/r, \quad (3)$$

where  $r$  is the exponential growth rate of the epidemic [11].

### 2.3 Model implementation

For each district, the exponential growth rate was estimated from the best-fit solution of the cumulative confirmed cases. For the estimation of the basic reproduction number  $R_0$ , the mean latent phase (incubation period) was considered to be 4 days as estimated from real data for the first cluster of COVID19 cases recorded in Pune in March 2020 (records available at the authors’ institution) (Table 1). The average “onset to isolation” period,  $1/\theta$ , is considered to be 5.2 days as measured in Pune in March 2020 (Table 2). The “onset to isolation” time is referred to as the ‘detection time’ in publications from China [1].

Data warehousing were performed in MS Excel. All calculations were performed in R package.

### 2.4 GIS analyses and visualization

District-wise list of  $R_0$  and doubling time ( $\tau$ ) were prepared as attribute tables in Q-GIS v 3.14 ( $\pi$ ) and distribution maps were generated. All maps are displayed as per the norms of Government of India (Ministry of Earth Sciences).

## 3 Results

In the present paper we have studied the spread of COVID-19 in the districts of India. Figure 1 describes the spread of COVID-19 covering various districts. While at the end of January 2020 only one district reported a single imported case, by the end of February two more districts reported cases. Then, numbers of cases were reported from various districts including local cases (due to contact with travelers) from the month of March onwards. The number of affected districts grew with time as: 204 in March, 273 in April, 169 in May, 57 in June, 8 in July and 2 in August totaling the coverage of 713 out of 717 districts of India by 31st August 2020 (Fig. 2). However, two districts were affected late. Kurung Kumey (Arunachal Pradesh) and Lakshadweep Is. recorded their first COVID-19 cases in 1st September 2020 and 18th January 2021 respectively. Nicobar Island (Andaman & Nicobar Is) has not recorded

**Table 1** Estimation of latent period for COVID-19

Patient ID	Exposure to onset (latent period, days)	Avg. latent period (1/k)
II	2	3.666 ~ 4 days
III	6	
IV	3	

**Table 2** Estimation of onset to isolation period for COVID-19

Patient ID	Onset-to-isolation period (days)	Avg. "Onset-to-Isolation" duration (1/θ)
I	7	5.2 days
II	6	
III	3	
IV	6	
V	4	

any case till 1st March 2021. There is no data available from the Gilgit-Baltistan region.

For each district the Basic reproduction number,  $R_0$  and the epidemic doubling time ( $\tau$ ) have been estimated. Figure 3 provides the best-fit solution from the analyses for the district of Hazaribagh, Jharkhand state as a representative data. The intrinsic growth rate ( $r$ ) of the epidemic was determined from the exponential growth of the cumulative number of cases using Eq. (1).  $R_0$  has been calculated using Eq. (2). The doubling time was estimated using Eq. (3). Figure 4 provides a distribution map of  $R_0$  covering the 717 districts of India. It should be noted that the lowest value,  $R_0 = 1.13$  is recorded for Jabalpur (Madhya Pradesh state), while the highest value  $R_0 = 7.7$  was recorded for three districts: Sipahijala (Tripura state), Ganjam (Odisha state) and Mahasamund (Chhattisgarh state). Figure 5 represents the distribution of districts (by number) in the range of  $R_0$  values. 144 out of 717 districts (20%) recorded  $R_0$  in the range 1–2 while 256 districts (35.7%) in the range 2–3, followed by 163 districts (22.7%) in the range 3–4, followed by 90 districts (12.6%) in the range 4–5. Thirty-nine districts (5.4%) recorded  $R_0$  in the higher range 5–6, and a further 13 districts (1.8%) recorded in the range 6–7. Only 8 districts (1.1%) recorded  $R_0$  in the high range  $\geq 7$ . There were a total of 6 districts (0.8%) which recorded less than 40 isolated cases at different time points across 12 months and no exponential increase in cumulative cases. For these districts the value of Basic reproduction number is considered as  $R_0 = 0$  as no local transmission or outbreaks occurred (Table 3). We have identified 8 districts, which became hotspots, with very intense transmission initially,  $R_0 \geq 7$  (Table 1). The district-wise calculation of the doubling time of epidemic size has been estimated (Fig. 6). Three districts recorded the fastest growth and the lowest doubling time  $\tau = 1.7$ , namely, Sipahijala (Tripura state), Ganjam (Odisha state) and Mahasamund (Chhattisgarh state). Jabalpur (Madhya

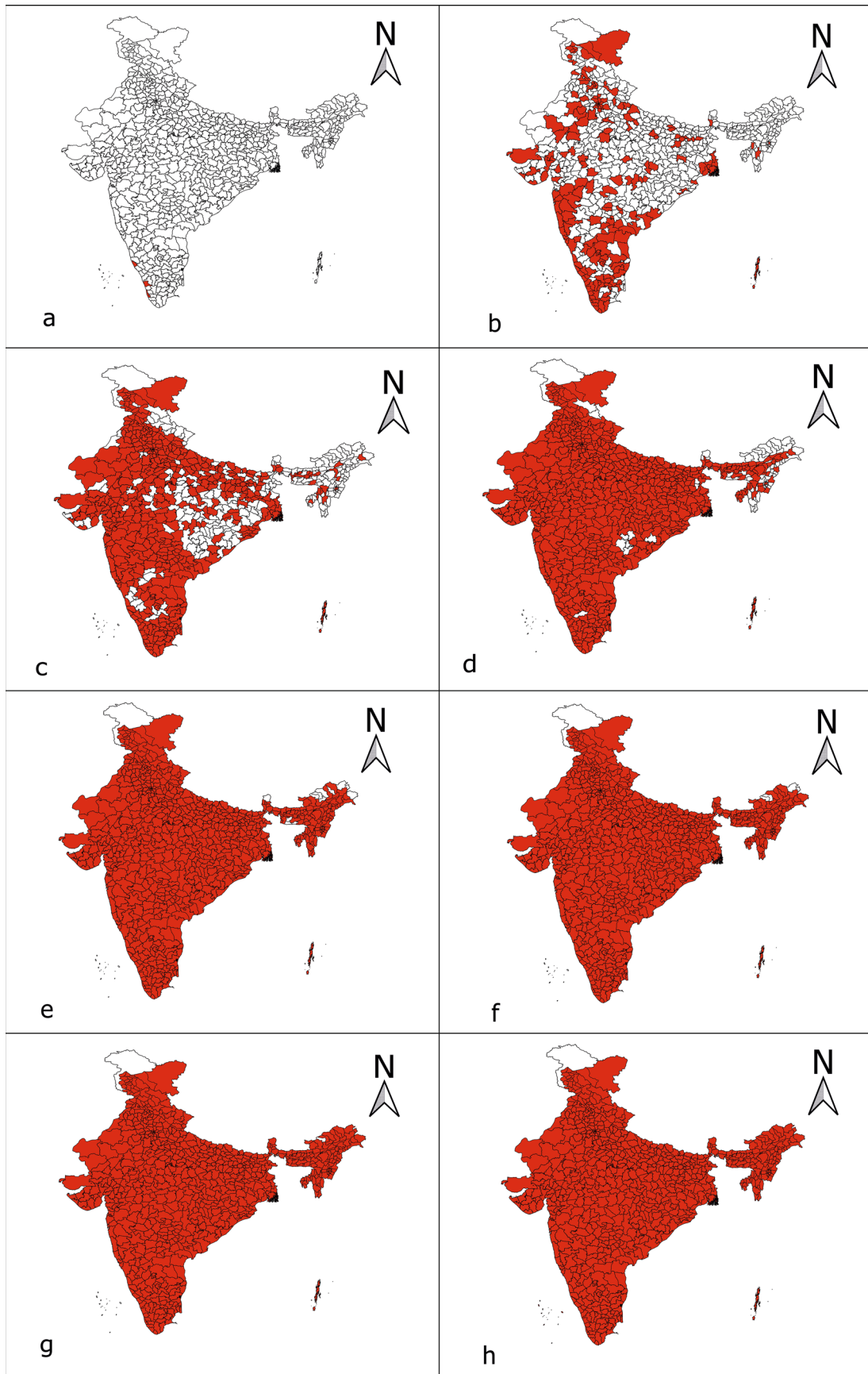
Pradesh state) recorded the highest doubling time (slowest growth)  $\tau = 46.2$  days.

A ranking of districts by total number of cases (cumulative cases) for the first six months (August 2020) is represented in Fig. 7. As on 1st March 2021, the following ten districts were found to be worst affected: New Delhi (639,464), Pune (410,699), Bengaluru Urban (405,847), Mumbai (326,772), Thane (280,947), Chennai (235,721), Nagpur (152,649), Kolkata (129,481), Nashik (128,528), and East Godavari (124,457).

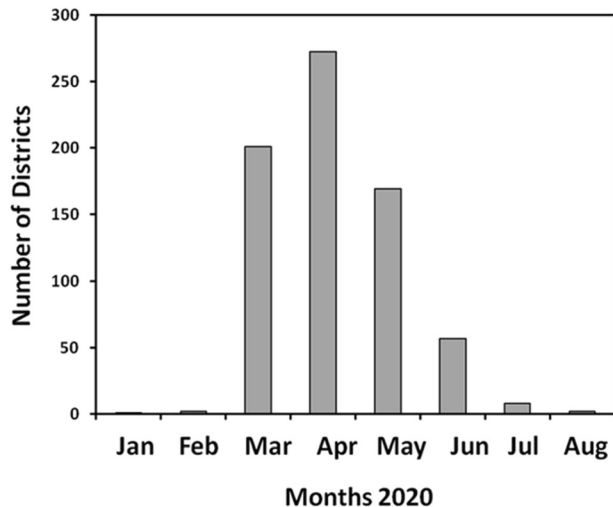
## 4 Discussion

Estimation of epidemiological parameters like Basic reproduction number,  $R_0$  has gained importance with the progress of the COVID-19 pandemic considering its implications for public health management. It may be considered as a "magic number or conundrum" because  $R_0$  is not an intrinsic property associated with any infectious pathogen. Rather, it is estimated by various methods taking into account the factors as: duration of contagiousness, the likelihood of passing on infection per contact between infected and susceptible individuals (transmissibility and meaningful contacts), and the contact rate between individuals in a population. Other factors may be socio-economic parameters which may vary based on the study [13].  $R_0$  is widely accepted as an important parameter that determines severity of spread of any viral disease [11, 12].

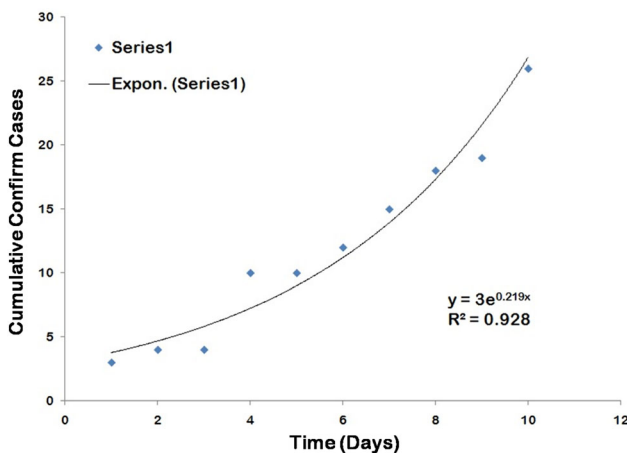
In the present study we have estimated the  $R_0$  for each district of India. The spread of COVID-19 was rapid. Starting with two districts in February 2020, it rapidly covered 201 districts in March, 273 in April, 169 in May and 57 in June, covering 97% of India (districts) by 30th June 2020. A few far-flung districts in the Himalayas were also affected later. By 1st March 2021, almost all except 3 districts were affected. It has been observed that a major



**Fig. 1** Spread of COVID-19 in India covering the districts from 1st February 2020 to 1st March 2021. **a** Till 29th February 2020, **b** till 31st March 2020, **c** till 30th April 2020, **d** till 31st May 2020, **e** till 30th June 2020, **f** till 31st July 2020, **g** till 31st August 2020 and **h** till 1st March 2021



**Fig. 2** Number of districts affected with new cases: month-wise distribution



**Fig. 3** Best-fit solution for the exponential growth of the cumulative confirmed cases (Hazaribagh, Jharkhand)

chunk of districts (34.8%) recorded  $R_0$  in the range 2–3, which is comparable to that reported from Italy [14].

Eight districts recorded very high value of  $R_0$  ( $> 7$ ) in their respective initial phases: Sipahijala, Ganjam, Mahasamund, Jamtara, Mungeli, Chitaurgarh, Nawashahr and Hassan. In all these districts, the doubling time was extremely low: 1–2 days. In Sipahijala, the cumulative number of confirmed cases (epidemic size) grew from 5 to 181 (10 days) and 365 (15 days), while in Ganjam it grew from 2 to 172 in 10 days. In Mungeli it grew from 1 to 82

cases in 10 days, while in Mahasamund, cases grew from 1 to 51 in similar duration. In Jamtara, the epidemic size grew from 2 to 54 in 9 days, while in Chitaurgarh, it rapidly increased from 1 to 90 in 10 days. In Hassan, the epidemic size grew from 1 to 55 in 10 days and to 101 in 15 days. In Nawashahr, epidemic size increased from 1 to 20 in 7 days. In all these districts, outbreaks started due to the migrant workers coming home. Though the country was under lockdown, special arrangements were made by state and central governments to transport migrant workers to their native places [20, 21]. The economy of these districts are mostly agriculture based and lacks industry, forcing skilled workforce to work in different parts of India. Sepahijala, located in North-East India, is partly forested with population preferring traditional bamboo/mud houses with cramped accommodation [22]. Similarly, outbreaks in Ganjam, Mungeli, Jamtara and Hassan districts are linked to arrival of migrants [23–26]. In case of Chittorgarh, the outbreak was driven by a super-spreader shopkeeper who kept shop open while being symptomatic and came in contact with  $> 300$  individuals [27]. In Nawashahr, which is known as the NRI belt due to large part of the population working abroad, the super-spreading event started due to international migrant workers coming home in first week of March 2020 [28].

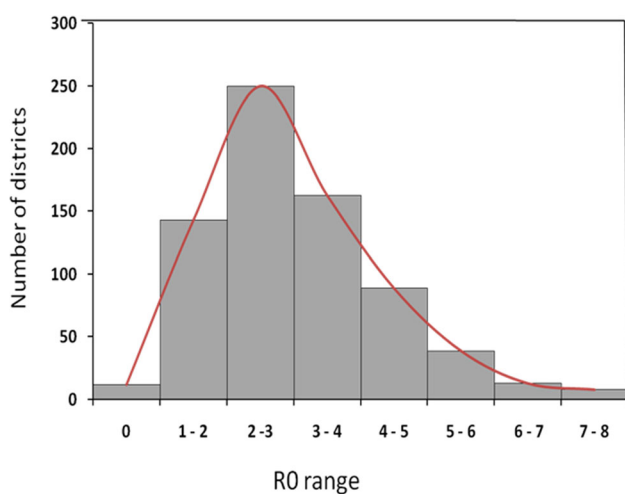
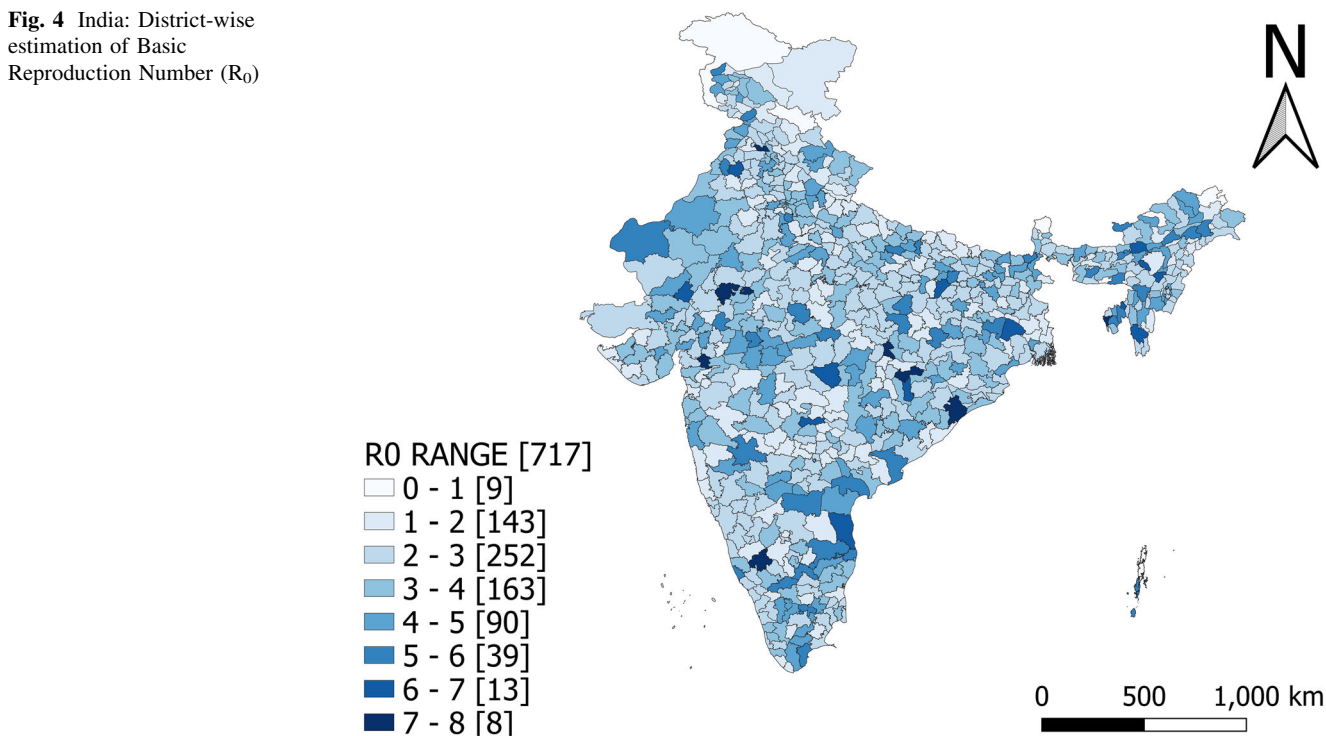
Such rapid growth in epidemic size were observed in Wuhan and Hubei in China in the early phase [1]. Since the outbreak of COVID-19 in Wuhan and its rapid spread elsewhere, efforts have been made to determine  $R_0$  in various settings in different countries. Variability is expected in the reported values due to the choice of estimation methods. Estimates based on Susceptible-Exposed-Infectious-Recovered (SEIR) or related models of transmission (that included a definite incubation period or latent period) indicate a range from  $R_0 = 3$ –7, for China and elsewhere [18].

The epidemic doubling time is less when there is rapid spread, that is, if the  $R_0$  is high. Majority of the districts in India (413 out of 717, 57.6%) recorded a doubling time of 2–4 days, which is comparable to most of the European nations and Iran [29–31]. This indicates intense spread.

In our analyses, we considered each district in their respective initial phases. Clusters of adjacent districts having high  $R_0$  did not occur. Many factors contributing to the spread of COVID-19 in India included: (a) imported cases (travelers from abroad returning to hometown or place of work (March 2020, when travel restrictions were not in place), (b) internal migration of people by inter-state travel [20], (c) mass migration of laborers or migrant workers (including the unorganized sectors) in April and May [20] and (d) super-spreading events like religious congregations in March 2020 [32]. India has implemented lockdown and interventions aimed at social distancing in



**Fig. 4** India: District-wise estimation of Basic Reproduction Number ( $R_0$ )



**Fig. 5** Distribution of the number of districts covering the ranges of  $R_0$  values

April 2020 and gradually eased the same in phases [33]. However, the spread in various districts continued because of any or combinations of the factors mentioned above. Also, it should be noted that India is very diverse in terms of climate, ethnicities and socio-cultural behaviors/practices. Hence, the implementation of nation-wide restrictions may not have been uniform across all districts.

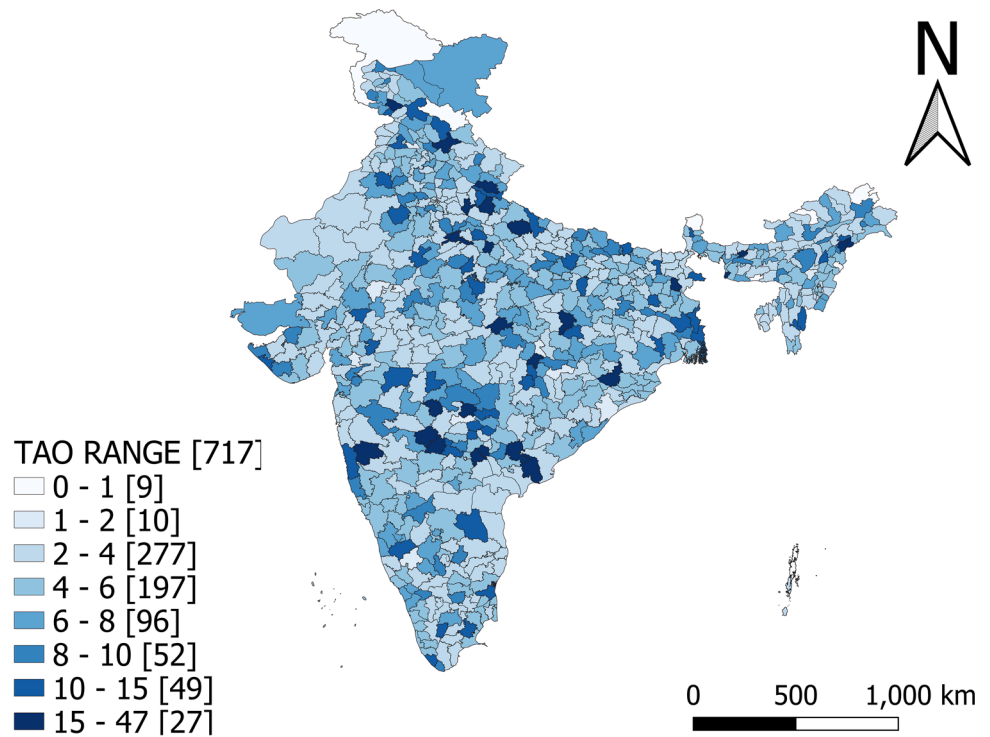
## 5 Conclusion

In the present study we have employed GIS to understand the spread of COVID-19 in India. Overall, we found that the COVID-19 has spread to 713 out of 717 districts of India within a span of 5 months. Estimation of the epidemiological parameters indicated moderate to intense transmission, which is at par with the global average and

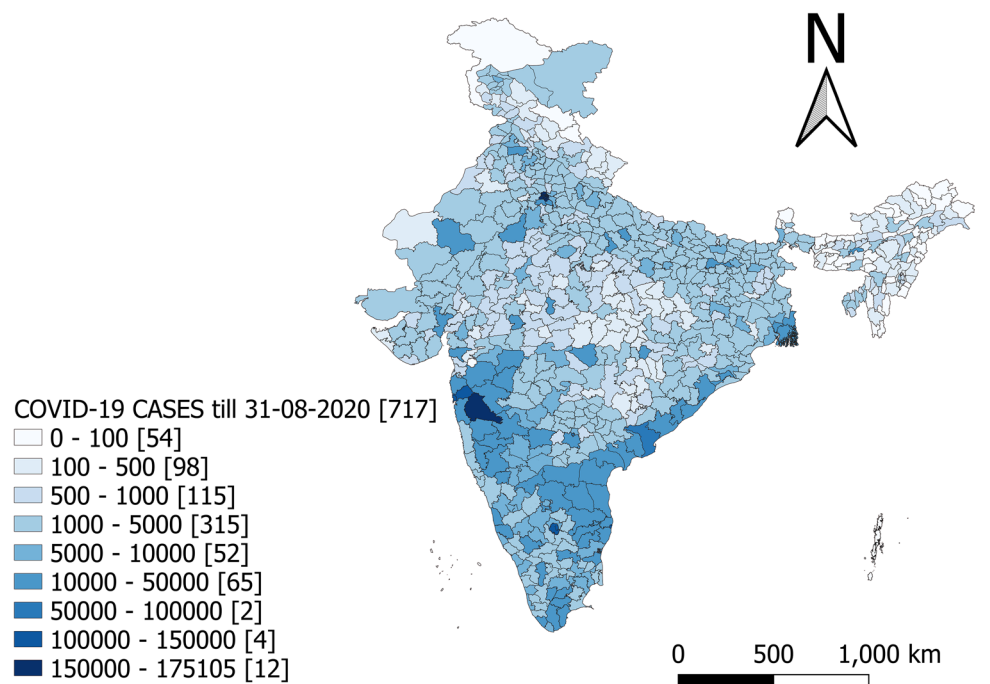
**Table 3** List of districts with  $R_0 = 0$

State	District	$R_0$	Tao	Date of first case	Total cases till 1st March 2021
Andaman and Nicobar	NICOBAR	0	0	–	0
Andaman and Nicobar	North and Middle Andaman	0	0	3/27/2020	17
Jammu & Kashmir	Gilgit and Baltistan	0	0	–	0
Arunachal Pradesh	Upper Dibang Valley	0	0	8/19/2020	23
Arunachal Pradesh	Kra Daadi	0	0	8/26/2020	37
Nagaland	Longleng	0	0	6/23/2020	19

**Fig. 6** India—District-wise estimation of outbreak doubling time ( $\tau$ ) in the initial phase



**Fig. 7** Ranking of districts by cumulative number of cases for the first six months (till 31st August 2020)



China. We found that the spread COVID-19 was not uniform across the districts of India.

**Author contributions** PS and PA conceptualized the study. NMA and AAP contributed in data acquisition and analyses with GIS technology, PS contributed in mathematical modelling and analyses. BVT and PS contributed in interpretation of results. BVT and PS

wrote the manuscript. PA contributed in reviewing and editing the manuscript.

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**Declarations**

**Conflict of interest** The authors declares that that they have no conflict of interest.

**Ethics Approval** The authors have no ethical approval to declare.

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