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Research article

Evaluation of prevention and control interventions and its impact on the epidemic of coronavirus disease 2019 in Chongqing and Guizhou Provinces

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Abstract: The outbreak of coronavirus disease 2019 (COVID-19) in Wuhan, which is caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), is still severe. In order to optimize the epidemic response strategy, it is urgent to evaluate the implemented prevention and control interventions (PCIs). Based on the reported data of Chongqing and Guizhou Provinces, the phased dynamic models of COVID-19 were constructed, the average intensity of the existing PCIs (from January 25 to March 2) was estimated in these two provinces. The results indicate that both provinces have carried out better control of the infected, but there are still differences in the intensity of control for people who need close observation. Especially in Chongqing, the estimated strength is significantly smaller than that in Guizhou. Furthermore, qualitative evaluations on the epidemic of COVID-19 under different PCIs scenarios suggest that containment strategy is still necessary to ensure the safety of resumption of work and school, and quarantining the city of Wuhan is an important and effective containment strategy to reduce the epidemic in other provinces.

Keywords: severe acute respiratory syndrome coronavirus 2; coronavirus disease 2019; dynamic model; prevention and control interventions

1. Introduction

Since December 31, 2019, the outbreak of coronavirus disease 2019 (COVID-19) in Wuhan City, Hubei Province of China, has been confirmed to be caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) [1]. Now, COVID-19 has become a sudden and serious problem on public health and prevention and control interventions (PCIs) in other cities of China, as well as internationally [2]. Based on the data at the beginning of the outbreak (before January 24), some dynamic models have been proposed to give opinions and peak prediction on the transmission rate of the epidemic, which may provide important reference for making epidemic preventing policies [3–5].

To avoid further deterioration of the epidemic, Wuhan has been cut off from the rest of China since January 23, 2020. Other regions in China, including Chongqing and Guizhou Provinces, have also adopted different levels of travel restrictions since Chinese New Year's Eve (January 24, 2020). In fact, Tang et al. (2020) estimated the impact of the closure of Wuhan on the epidemic situation in Beijing [5], and the results showed that the closure of Wuhan played a significant role in the PCIs of the national epidemic. However, the study on the effectiveness of the travel restriction strategies, which have been implemented by various provinces, is still scarce till now, especially in the situation where the strategies of different cites may not be completely consistent. In this paper, we will focus on Chongqing and Guizhou Provinces, which are also our hometown in Southwest China. From the beginning of Chunyun, or spring migration (January 10, 2020), taking Chinese New Year's Eve as the dividing point, we use the phased dynamic model to qualitatively estimate the intensity of PCIs in the two provinces, and further make a qualitative evaluation on the epidemic of COVID-19 under different PCIs scenarios. These results were also submitted to the Health Committees of the two provinces, which provide assistance for the government to formulate PCIs policies and resource scheduling.

2. Materials and methods

2.1. Data collection

From January 10 to March 2, 2020, the number of infected/confirmed patients and the number of isolated/monitored people per day were obtained from the daily report of epidemic situation on the official websites of Health Committees of Chongqing and Guizhou provinces [6, 7].

The total initial susceptible population is taken as the total population of Chongqing and Guizhou provinces respectively. Although the concept of "resident population" is often used, the concept of "household registered population" is actually adopted in this study. The reason is that this period coincides with the traditional Chinese New Years, and the Chunyun begins on January 10. As a result, the population of all parts of the country will return to the place where the household registration is located, so it will be more accurate to describe the total population of the local area with the number of household registered population. According to the statistical yearbook of Chongqing City (2019) [8] and the statistical yearbook of Guizhou Province (2019) [9], we know that the household registered population of Chongqing and Guizhou provinces are 34 millions and 45 millions respectively.

Considering the fact that Wuhan is the origin of COVID-19 in China, through the migration scale index provided by Baidu migration [10], we estimate the daily population from Wuhan to Chongqing and Guizhou. Concretely, during the period from January 10 to January 24, 2020 (after the closure of Wuhan, one-day delay is considered), using the migration scale index of Wuhan in Hubei Province and comparing with the migration scale index of Chongqing and Guizhou Provinces, we can calculate the daily proportion of the population from Wuhan to Chongqing and Guizhou. Then, by comparing the migration scale index of Wuhan, we can get the proportion of daily migration scale in the total migration population. According to the data from Hubei Provincial People's Government Press Conference, the total migration population of Wuhan during this period is estimated to be 5 million. Finally, we obtained the number of people who returned from Wuhan to Chongqing and Guizhou every day during January 10 to 24, 2020, which is listed in Table 1.

Table 1. Number of people returning from Wuhan to Chongqing and Guizhou (ten thousand).

Time	Jan 10	Jan 11	Jan 12	Jan 13	Jan 14	Jan 15	Jan 16	Jan 17
Chongqing	0.4413	0.4086	0.3754	0.3450	0.3517	0.4099	0.3919	0.3829
Guizhou	0.3041	0.2588	0.2437	0.2542	0.1967	0.1571	0.1594	0.1479
Time	Jan 18	Jan 19	Jan 20	Jan 21	Jan 22	Jan 23	Jan 24	
Chongqing	0.4410	0.4305	0.4753	0.6047	0.5546	0.5018	0.2260	
Guizhou	0.1563	0.1569	0.1684	0.1838	0.1600	0.1455	0.0648	

2.2. Dynamic model of COVID-19

At present, according to the primary epidemiological properties of COVID-19, many public health interventions, such as quarantine, isolation, hygiene precaution and so on, have been implemented all over China. To simplify, we divide the total population in Chongqing and Guizhou provinces into five compartments, named as Wuhan returnees (W), locally susceptible (S), people who need to be closely observed (C, including all people involved in the public health interventions, even potential close contacts), infected/diagnosed (I) and recovered (R, including death). Note that COVID-19 is a sudden new malignant infectious disease and its epidemiological characteristics are not clear enough. The strategy adopted at that time was to isolate as possible as all those who had contact with Wuhan returnees W, close contacts C and the infected I. As a result, we first have the following relationship during January 10 to 24, 2020,

$$\begin{cases} \dfrac{dS}{dt} = \gamma C - \beta_0 S(1-\varepsilon-\eta_1)W(t) - \beta_1 SC - \beta_2 SI, \\ \dfrac{dC}{dt} = \varepsilon W(t) + \beta_0 S(1-\varepsilon-\eta_1)W(t) + \beta_1 SC + \beta_2 SI - \eta_2 C - \gamma C, \\ \dfrac{dI}{dt} = \eta_1 W(t) + \eta_2 C - \mu I, \\ \dfrac{dR}{dt} = \mu I, \end{cases} \tag{2.1}$$

where ε and η_1 are the average ratio of closely observed returnees and infected/diagnosed from Wuhan respectively, η_2 is the average rate of confirmed from closely observers, β_i, $i = 0, 1, 2$, are the average effective contact rate between locally susceptible and Wuhan returnees, closely observers and infected/diagnosed respectively. As the usual close observation period for 2019-nCoVSARS-CoV-2 is about 14 days, $\gamma = 1/14$. Note that μ contains two parts, one is the average discharge rate and the other is the average mortality rate. At the beginning of the outbreak, due to the novelty of COVID-19 and in order to reduce the number of estimated parameters, the quotient of the sum of the number of discharge and death in the whole country divided by the total number of infected people in the whole country was used as the approximation of parameter μ in model (2.1). Thus, according to the reported data on January 30, we have $\mu = (129 + 170)/7749$. Note that COVID-19 in Chongqing and Guizhou are imported. The initial locally susceptible of model (2.1) is set as the household registered population, i.e., $S(0) = 34$ millions in Chongqing and $S(0) = 45$ millions in Guizhou. The other initial values of model (2.1) are $C(0) = I(0) = R(0) = 0$.

Due to the closure of Wuhan, no one returned from Wuhan to Chongqing and Guizhou since January 25. Thus, after January 24, we have $W(t) = 0$, and model (2.1) can be reduced as

$$\begin{cases} \dfrac{dS}{dt} = \gamma C - \beta_1 SC - \beta_2 SI, \\ \dfrac{dC}{dt} = \beta_1 SC + \beta_2 SI - \eta_2 C - \gamma C, \\ \dfrac{dI}{dt} = \eta_2 C - \mu I, \\ \dfrac{dR}{dt} = \mu I. \end{cases} \tag{2.2}$$

For (2.2), in order to measure the intensity of PCIs after January 24, we decompose the average effective contact rate (β_i) into the product of the risk of transmission per contact ($\beta_i^{'}$) and the average contact number by a person (k_i), i.e., $\beta_i = \beta_i^{'} \cdot k_i$, in which $k_i \geq 0$ is the measure of PCIs, and smaller k_i means greater PCIs, $i = 1, 2$. According to [4], before January 24, i.e., before taking strict travel restriction strategy in areas other than Wuhan, we roughly assume $k_1 = 10$ and $k_2 = 5$ because there are more restrictive control in infected/diagnosed than that in closely observers. In addition, with the further understanding of the disease, diagnosis method, discharge rate and mortality will change significantly over time, so parameter η_2, μ also need to be re-estimated by (2.2).

2.3. Simulations

An adaptive Metropolis-Hastings algorithm was conducted to carry out the Markov Chain Monte Carlo (MCMC) procedure to estimate the undetermined parameters. The algorithm runs for 3×10^6 iterations with a burn-in of 10^6 iterations, with the Geweke convergence diagnostic method employed to assess the convergence [11].

Concretely, the reported daily incidence from January 10 to 24 was first used to obtain the estimate of ε, η_i ($i = 1, 2$) and β_j ($j = 0, 1, 2$) in (2.1). Here the prior information were given as $\varepsilon \in [0, 0.01)$, all η_i and β_j are nonnegative constants, and the proposed density was chosen by a multivariate normal distribution. Then, taking $k_1 = 10$ and $k_2 = 5$, we can further obtain the estimate of $\beta_i^{'}$ ($i = 1, 2$). Lastly, keeping the parameters unchanged except for k_i, η_2, μ, and using the daily incidence from January 25 to March 2 and (2.2), we can obtain the estimate of the average intensity of PCIs (k_i, $i = 1, 2$) and updated η_2, μ after January 24.

2.4. PCIs scenarios

Note that government started to take many measures in response to the epidemic of COVID-19 in Chongqing and Guizhou. To mimic the impact of different intensity of PCIs, using the above fitting parameters, we assume the following several different PCIs scenarios:

(1) If the existing intensity of PCIs is continued, will the epidemic be contained? If so, what is the peak of daily incidence and when is the peak time?

(2) Along with the increased intensity of PCIs, because the information is clear and the quantity is relatively small for the infected/confirmed (I), the prevention and control of them is relatively easy to implement. Considering an extreme situation, once diagnosed, we can completely cut off their contact with susceptible, i.e. assuming $k_2 = 0$. Then let k_1 change from 0 to 4, which corresponds to completely ($k_1 = 0$) or partially ($k_1 > 0$) cutting off the contact between the close observer (C) and susceptible. What will happen on the trend of the epidemic? Including the peak of daily incidence and corresponding peak time.

(3) If there is no shutting down Wuhan, simply take the average number from January 10 to 24 (Table 1) as the estimated number of people returning from Wuhan to Chongqing and Guizhou every day, how will the epidemic develop? In other words, what will happen with (2.1) alone?

3. Results

3.1. Fitting model (2.1) with daily incidence before strong measures

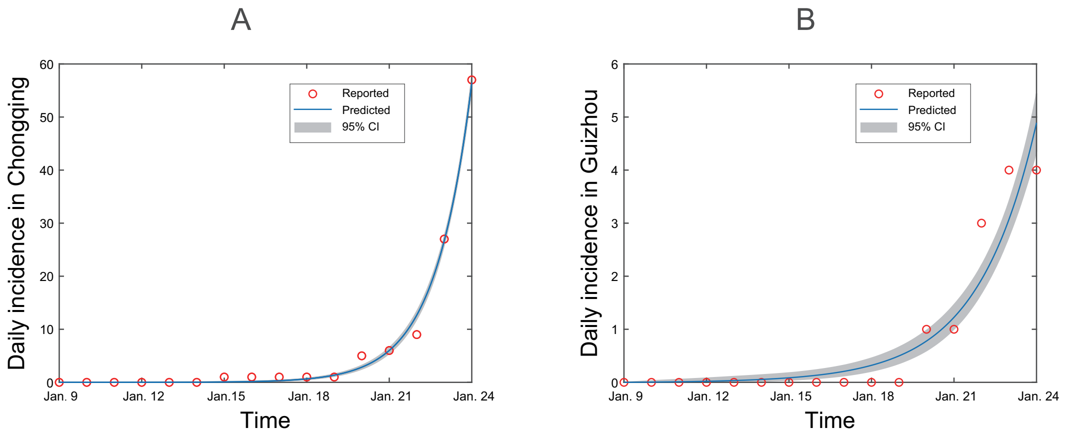

Figure 1. Illustration of the fitting result of (2.1) under estimated parameters before strong measures (January 24) in Chongqing (A) and Guizhou (B). The solid blue line represents the model-predicted daily incidence and the reported data are shown as red circle. Gray areas represent the 95% confidence interval (CI) of the model prediction.

Table 2. Estimated parameters of model (2.1).

Parameter	Values in Chongqing	Values in Guizhou
ε	$5.000 \times 10^{-7}(2.188 \times 10^{-7}, 9.395 \times 10^{-7})$	$8.342 \times 10^{-6}(3.667 \times 10^{-6}, 1.562 \times 10^{-5})$
η_1	$1.362 \times 10^{-7}(5.191 \times 10^{-8}, 3.747 \times 10^{-7})$	$1.386 \times 10^{-6}(5.282 \times 10^{-7}, 5.061 \times 10^{-6})$
η_2	$0.105(0.102, 0.108)$	$1.709 \times 10^{-2}(1.610 \times 10^{-2}, 1.810 \times 10^{-2})$
β_0	$1.382 \times 10^{-14}(6.331 \times 10^{-15}, 2.380 \times 10^{-14})$	$3.146 \times 10^{-13}(1.366 \times 10^{-13}, 6.214 \times 10^{-13})$
β_1	$1.405 \times 10^{-8}(5.739 \times 10^{-9}, 2.474 \times 10^{-8})$	$8.176 \times 10^{-9}(3.390 \times 10^{-9}, 1.153 \times 10^{-8})$
β_2	$9.843 \times 10^{-8}(1.804 \times 10^{-8}, 1.604 \times 10^{-7})$	$1.166 \times 10^{-7}(2.083 \times 10^{-8}, 2.532 \times 10^{-7})$

According to (2.1) and the daily incidence before January 24 in Chongqing and Guizhou, we employed an adaptive Metropolis-Hastings algorithm to carry out extensive MCMC simulations. Figure 1 illustrates the best-fit simulation of (2.1) with the fitted parameters, which indicate that the model results were in good agreement with the reported data before strong measures. The median values of the estimated parameters and their corresponding first and third quartiles (Q1-Q3) are listed in Table 2, and their distribution was depicted in Figure 2.

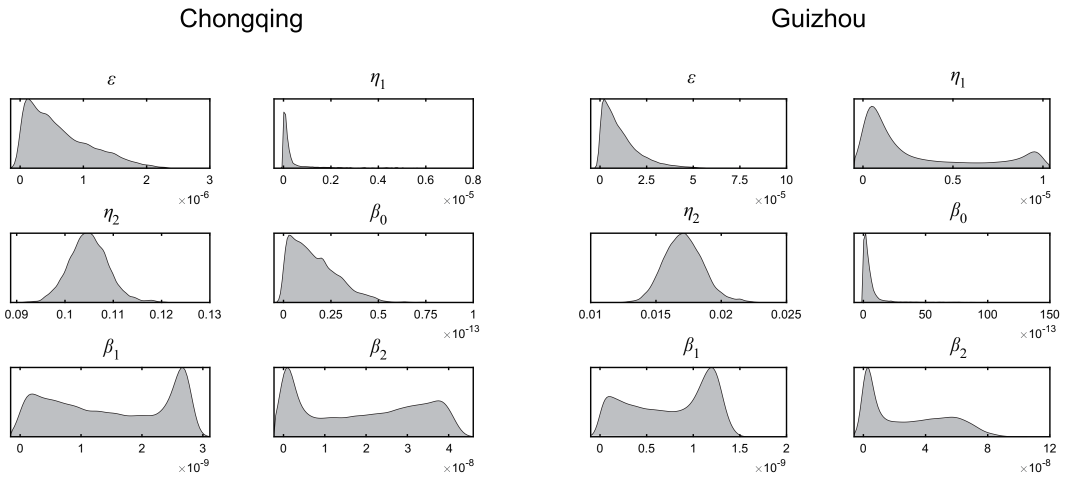

Figure 2. Distribution of the fitted parameters in model (2.1) in Chongqing and Guizhou before strong measures (January 24). The algorithm runs for 3×10^6 iterations with a burn-in of 10^6 iterations, and the Geweke convergence diagnostic method was employed to assess convergence of chains. The initial values of each parameter were positive and randomly selected.

3.2. Estimating average intensity of PCIs after strong measures

According to the daily incidence between January 25 and March 2, using model (2.2) and the above-mentioned methods, we can obtain the average intensity of PCIs after January 25. The results are $k_1 = 3.2469$ and $k_1 = 2.5333$ in Chongqing and Guizhou respectively, and their k_2 are almost zero since the order of magnitude is -10. In addition, parameters η_2 and μ are updated to 0.1518 and 0.0463 in Chongqing, 0.0797 and 0.0360 in Guizhou. Figure 3 illustrates the best-fit simulation of (2.2) with the fitted average intensity of PCIs.

3.3. Qualitative assessment under different PCIs scenarios

If the existing intensity of PCIs is maintained, Figure 3 indicates that COVID-19 in Chongqing and Guizhou can be eventually controlled, the estimated peak of daily incidence in Chongqing and Guizhou will be up to hundreds and near hundred respectively, which arrived at the early of February.

If the infected/diagnosed are completely isolated, i.e., $k_2 = 0$, let k_1 changes from 0 to 2 in steps of 0.5, Table 3 gives the qualitative assessment of the epidemic under different intensity of close observers, and Figure 4 show a visual representation of the results. The results indicate that the peak time lies in the early of February and the disease will disappear in about five months after January 9.

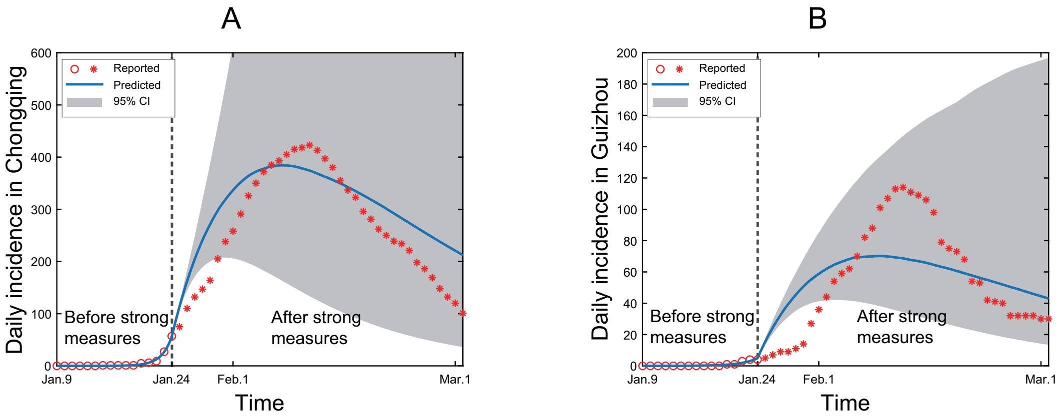

Figure 3. Illustration of the fitting result of (2.2) under estimated average intensity of PCIs and updated parameters η_2, μ after strong measures in Chongqing (A) and Guizhou (B). Red circles and stars represent the reported data before and after Jan 24 (black dash line). The solid blue line represents the model-predicted daily incidence, and gray areas represent the 95% CI of the model prediction.

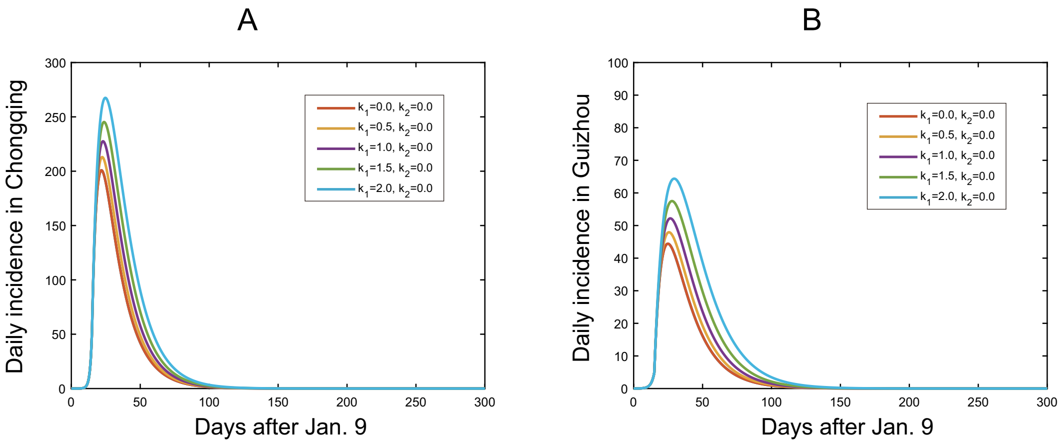

Figure 4. Illustration of the estimated peak of daily incidence and peak time if $k_2 = 0$ and k_1 changes from 0 to 2 in steps of 0.5 in Chongqing (A) and Guizhou (B).

Table 3. Prediction under $k_2 = 0$ and different k_1 scenarios in Chongqing and Guizhou.

k_1	Chongqing			Guizhou		
	Peak time	Peak daily incidence	Accumulative incidence	Peak time	Peak daily incidence	Accumulative incidence
0.0	Jan 31	201	340	Feb 3	44	81
0.5	Jan 31	213	373	Feb 4	48	91
1.0	Feb 1	228	416	Feb 5	52	105
1.5	Feb 2	245	473	Feb 6	58	124
2.0	Feb 3	267	550	Feb 7	64	153

If the PCIs of close observers is relaxed, i.e., let k_1 changes from 0 to 4 but $k_2 = 0$, Figure 5 further gives the corresponding curves of peak time, peak of daily incidence and accumulative incidence. The results indicate that taking more strong measures to close observers, i.e., the smaller k_1, is always beneficial to control COVID-19, which could not only significantly reduce the peak of the epidemic, but also reduce the final accumulative incidence. However, it is worth noting that with the increase of k_1, the peak time will suddenly and significantly increase at a certain k_1. When k_1 exceeds the certain critical value, the peak time will drop sharply, and the accumulative incidence will tend to almost all susceptible people, i.e., almost all people will be infected. This suggests that there will be a mutation in epidemic control if the intensity of the measures is not enough, which may bring greater challenges to the control of COVID-19.

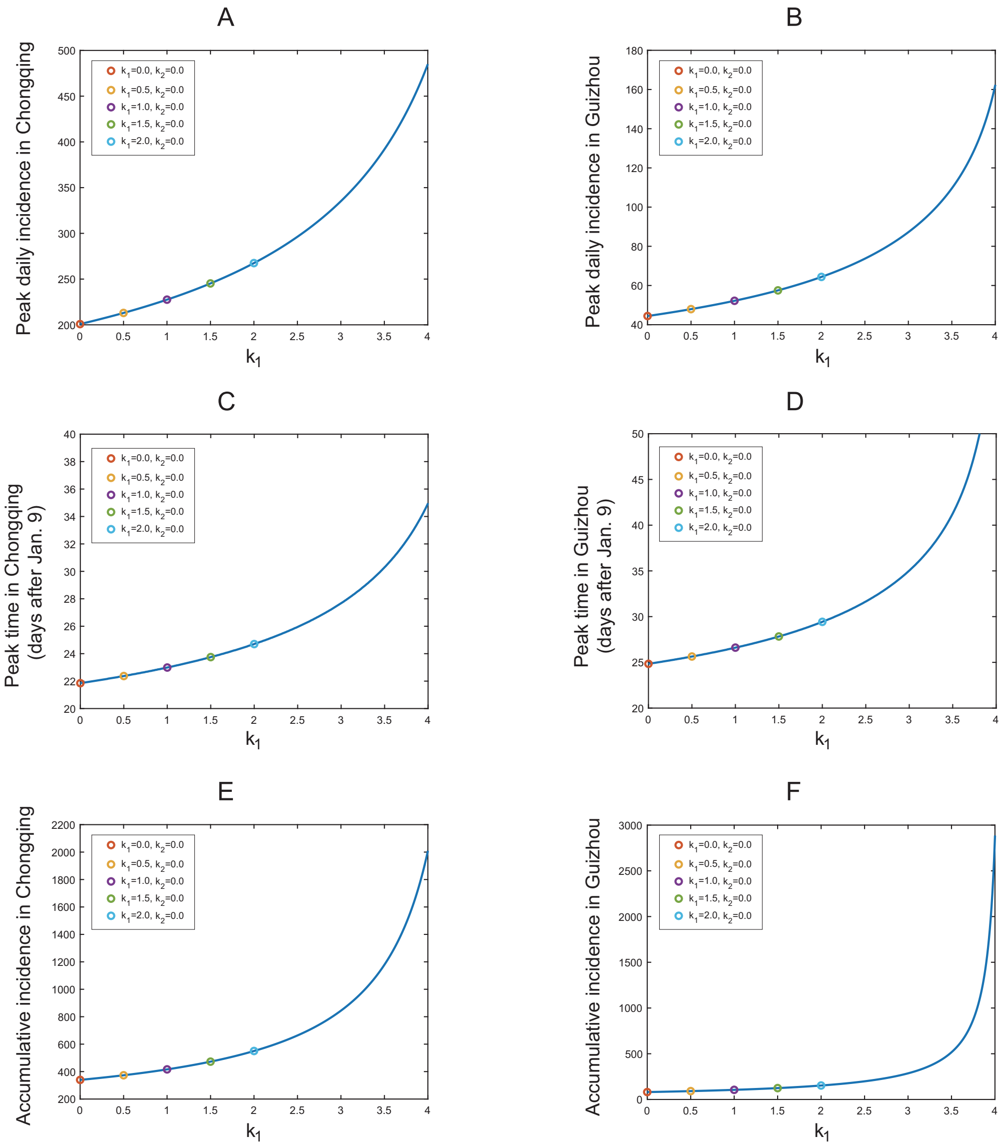

Figure 5. Illustration of the estimated curves of peak time, peak of daily incidence and accumulative incidence. Left panels (A, C and E) are the results in Chongqing, and right panels (B, D, and F) are the results in Guizhou.

Suppose that there is a continuous flow of people from Wuhan, i.e., Wuhan is not being cut off. Using model (2.1), we can find that the estimated peak of daily incidence in Chongqing and Guizhou will be up to millions (Figure 6). Comparing Figure 6 with Figure 3, we can conclude that the closure of Wuhan has played a crucial role in the control of COVID-19.

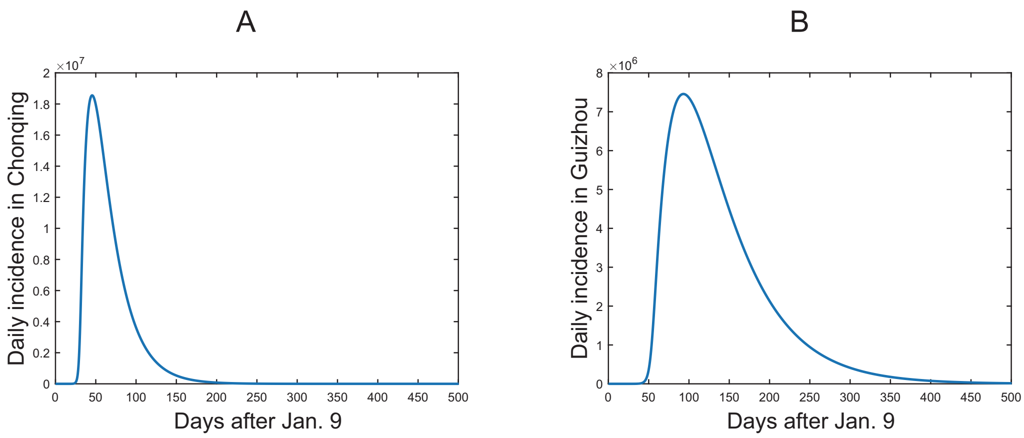

Figure 6. Illustration of the estimated peak of daily incidence and peak time if Wuhan is not being cut off under (2.1) and PCIs scenarios (3). (A) is the results in Chongqing, and (B) is the results in Guizhou.

4. Discussion and conclusion

On January 30, 2020, World Health Organization (WHO) has announced that COVID-19 is a Public Health Emergency of International Concern (PHEIC) [12]. At present, COVID-19 has been listed in the class B infectious diseases in China and managed according to class A [13]. The Chinese government has implemented a variety of strategies to curb the spread of SARS-CoV-2 and reduce the impact of the epidemic. Among them, reasonable prediction of medical service demand and evaluation of PCI are essential to fight against the epidemic, which can reduce the health and economic losses of the epidemic [14].

Based on the reported data, although some mathematical models [3–5] have been constructed to simulate the transmission capacity of the disease (such as the estimation of the basic reproduction number) and predict the epidemic scale (such as the total number of infections), the estimation and evaluation of PCIs have hardly been reported. In this study, based on the daily reported data of infected/diagnosed in Chongqing and Guizhou Provinces from January 10 to March 2, 2020, according to the characteristics of COVID-19 spread induced by the returnees before the closure of Wuhan, and taking January 25 as the demarcation point for the local government to take strong measures in response to the epidemic, we constructed dynamic model (2.1) and (2.2) before and after the closure and strong measures respectively. By introducing the parameters of the average daily contact number of the infected/confirmed patients and those who need close observation, we evaluated the effectiveness of the current PCIs in Chongqing and Guizhou. The results indicate that both provinces have carried out better control of the infected, but there are still differences in the intensity of control for people who need close observation. Especially in Chongqing, the estimated k_1 is significantly larger than that in Guizhou.

If the current PCIs remain unchanged, the time series of daily incidence in these two provinces are predicted by the models (Figure 3). Conversely, suppose that the government takes stronger measures, in particular, assuming that the infected/confirmed can be completely isolated, i.e., their daily average contact number is 0, we obtained the qualitative assessment on the impact of daily average contact number of people who need close observation under different scenarios (Table 3, Figures 4 and 5). Especially, the influence of shutting down Wuhan is also evaluated by comparing Figure 3 with Figure 4.

In conclusion, according to the simulation results of the model, we can draw the following conclusions and suggestions:

(1) For Chongqing and Guizhou Provinces, under current PCIs, although COVID-19 can be controlled, the elimination time is very long (about five months after January 9).

(2) In order to ensure the safety of resumption of work and school, the governments of these two provinces should take more strict PCIs, especially to those who need close observation. In other words, although the COVID-19 has passed the early stage of the epidemic, containment strategy is still necessary.

(3) From the national level, quarantining the city of Wuhan is an important and effective containment strategy to reduce the epidemic in other provinces.

Though the proposed dynamic models can provide qualitative assessment of the different PCIs scenarios, the present study still had certain limitations. For example, because not all people in C and W classes are infected, more details are worth considering in the dynamic models, such as the contact between C and I, whether the infected person is hospitalized, and so on. Furthermore, note that the case data is relatively small in Guizhou province. What is the effect of any demographic stochasticity? These will be left to us for future works.

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Conflict of interest

The authors declare that they have no competing interests.

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