COVID-19 in Kerala: analysis of measures and impacts

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COVID-19 in Kerala: analysis of measures and impacts

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In the absence of an effective vaccine or drug therapy, non-Pharmaceutical Interventions are the only option for control of the outbreak of the coronavirus disease 2019, a pandemic with global implications. Each of the over 200 countries affected[1] has followed its own path in dealing with the crisis, making it difficult to evaluate the effectiveness of measures implemented, either individually, or collectively. In this paper we analyse the case of the south Indian state of Kerala, which received much praise in the international media for its success in containing the spread of the disease in the early months of the pandemic, but is now in the grips of a second wave. We use a model to study the trajectory of the disease in the state during the first four months of the outbreak. We then use the model for a retrospective analysis of measures taken to combat the spread of the disease, to evaluate their impact. Because of the unusual aspects of the Kerala case, we argue that it is a model worthy of a place in the discussion on how the world might best handle this and other, future, pandemics.

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Introduction

The emergence of a novel coronavirus, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2)[2], has led to a global health emergency [3], with the resulting disease coronavirus disease 2019 (COVID-19) spreading globally. COVID-19 can manifest with no symptoms up to severe illness[4], with symptoms including respiratory disease, severe pneumonia[5] and in extreme cases death. The disease is particularly dangerous to those with underlying medical conditions and older people[4]. Non-Pharmaceutical Interventions (NPIs) have been the only tool available so far to control the virus spread[6,7].

India has been hit hard by COVID-19, reporting over 821,000 cases on 10th July, 2020[1] despite not having reached the peak of the outbreak[8]. In the South Indian state of Kerala, the pattern has been different from the rest of India. The state has a population of 33.3 million[9], but reported only 1,208 cases of COVID-19 as of 30th May 2020[1], of which the majority were linked to exposed or infected people travelling into Kerala from the rest of India or abroad. Countries of comparable sizes such as Canada (35.2 million[10]) reported 91,600 cases on the same day, with similar introduction date[1]. The aggressive implementation of NPIs in Kerala, including track and trace, quarantining, and lockdown, has been lauded as the predominant reason for Kerala's early success in avoiding a worse outbreak[11].

In this paper we use a susceptible-exposed-infected-recovered (SEIR) model to evaluate, retroactively, the impact of the actions taken in Kerala to contain the disease, in the four months since the first recorded appearance of the disease in Kerala on 30th January, 2020, and discuss implications for the future, in the light of the model results.

Kerala followed a multi-strand approach to contain the spread of COVID-19, from 30th January 2020 when a medical student returning from Wuhan (China) tested positive. The strategy was implemented in three stages:

Phase 1: initial stage (January 30 to March 24);

Phase 2: lock-down stage (March 24 to June 1); and

Phase 3: unlock stage (June 1 onwards).

During the phase 1, travellers coming from COVID-19-reported countries were monitored at all points of entry into the state; and suspected cases were placed under quarantine in government hospitals, and all identified primary contacts were placed under self-quarantine.

At the beginning of Phase 2, there were 109 confirmed cases. Within Phase 2, on 16th April the national government announced the identification of hotspot districts in every state in India, classifying the districts into red, orange and green zones, corresponding to the number of active cases in each district[12]. On 20th April lock-down was relaxed for districts in Kerala in the green and orange zones. Subsequently, a repatriation scheme was initiated through which 127,089 Keralites had returned to the state by 30th May[13]. Passengers coming from outside Kerala were quarantined for 14 days at home or at facilities provided by the government. Local health workers monitored adherence to quarantine at the individual level.

In Phase 3, travel restrictions were implemented in red zones only; public transport restarted operations; and offices and shops were allowed to open. The active cases in Kerala increased from 16 on 8th May to 1,231 on 9th June[13], though the spread of disease through contact was restricted to ~ 10%. The implementation of strict quarantine measures and public participation has been credited with the low rate of contact transmission.

The Kerala plan included: 1) testing the population according to World Health Organisation directives and strict quarantine of all cases suspected of infection; 2) implementation of travel bans across sub-state administrative (district) boundaries and state borders; 3) a public outreach campaign, "break the chain", focusing on hygiene; 4) use of citizen science for data collection and management[14]; 5) organisation of a special youth task force of 236,000 volunteers for supporting the more-vulnerable senior citizens and others under quarantine, with delivery of food, medicine and other needs[15]; and 6) arranging community kitchens to deliver cooked food to stranded migratory labourers and others in need. The overall approach was a decentralised and distributed one, with a clear plan of action at every level of administration, with full community engagement.

The Kerala COVID-19 model used in this work is based on the generic class of SEIR models, with additional partitioning of the population into hospitalised and out-of-hospital compartments, with a third dealing with people travelling into the state (Figure 1, see details in methods section). The model was fitted to observations. Variants of the model were then generated, to test the effects of (1) reduced testing; (2) no travel restrictions; (3) no out-of-hospital measures; (4) no in-hospital quarantine; and (5) all measures removed. Treatment of the out-of-hospital measures included consideration of the consequences of: no quarantine of out-of-hospital population with no lock-down; no track-and trace; and their combined effect (see methods section for further details).

Results

The reference model reproduces the time series of observations of COVID-19 cases and deaths with high fidelity (Figure 1). The snapshot outputs at the end of the run, on 30th May, also correspond well with the observed hospitalised cases and reproduce the low number of deaths (Table 1a). The maximum and cumulative modelled in-hospital cases are 527 and 1,273 respectively, which correspond to observed cases of 624 and 1,208 (see Table 1a). The

Kerala reference model predicts a total of 7 deaths between 30th January 2020 and 30th May 2020 (compared with 9 reported). The model admits that a proportion of infected people may not have been identified; and the 2,461 cumulative modelled cases (Table 1a) consist of the in-hospital infected population and the out-of-hospital, undetected, but infected, population (Figure SM-1). Comparison with the cumulative hospitalised cases suggests that there were many undetected cases outside the hospital as reported on 30th May. This was not always the case (Figure 2): according to the model, there were no undetected cases in the community between day 67 (7th April) and day 90 (29th April). Since all people who tested positive, or presented recognisable symptoms, were hospitalised, this result suggests that by the end of the simulation period, many cases were asymptomatic, or presented atypically. While it would be impossible to verify the number of out-of-hospital infected people, this result could help explain why the number of cases increased rapidly, once lock-down measures were relaxed.

Currently the state has 1,280 public hospitals and 2,062 private hospitals, giving a state-wide total of 99,227 hospital beds, of which 4,961 are intensive care unit beds, with 2,481 ventilators[16]. As of 30th May 2020, Kerala had not reached any of these thresholds. However, it shows a worrying trend, with the number of cases increasing from day 99, indicating both an increase in transmission rate as well as the intake of already-infected people into the state. Though the basic reproduction number $\mathcal{R}_0$ had dropped to 0.21 by 24th March, a value well below the threshold of one required for the number of cases to decline, it had risen far above the threshold value by 20th April, reaching 2.1 (close to its initial value 2.2 at the beginning of simulation, see Supplementary Material, Table SM-3). This is consistent with recent reports in mid-July, according to which community transmission was responsible for more newly-reported cases than the influx of infected people.

In the simulations which considered the impact of government measures, removing in-hospital quarantine had the most effect, with only the removal of all modelled government actions yielding a higher number of cases and deaths (see Table 1a and Figure 3 and Figure SM-2). Removing out-of-hospital measures also had a high impact on both death and cases. Increasing $\mathcal{R}_0$ (to simulate no track and trace) augmented the rate of increase, bringing it closer to the case of no in-hospital quarantine. Reduced testing and increasing the influx of people into the state also augmented infections and deaths, but at a less alarming rate than the no-quarantine cases.

Hence, the considerable effort by volunteers, health workers, government departments and the general public to enact the full quarantine had been amply rewarded, according to the model. Quarantining had reduced the transmission rate and stopped the spread from within hospital to out-of-hospital, as well as within the out-of-hospital population. Relaxing or removing quarantine would have overstretched Kerala's hospital facilities.

Due to the success of the initial actions taken by the government, with excellent response from the community, only a small proportion of the community had the virus (2,461) by 30th May, according to the reference model. These low numbers do not come close to the rate required for herd immunity (60% for an $\mathcal{R}_0$ of 2.5[17], or 55% for an $\mathcal{R}_0$ of 2.2 which occurs with track-and-trace) so that population immunity cannot be relied upon to slow infection. Without further decrease in the transmission rate, the outbreak, which was successfully stalled, has the potential to return in full force. For comparison with other countries, a snapshot at the end of May (Table 1b) shows a high level of success in Kerala, in keeping the number of infections down. But it is evident from the inferred $\mathcal{R}_0$ that relaxation came too early, and that longer-term control strategies are needed to prevent further escalation through community transmission[18].

Discussion

This work would not have been possible without the meticulous book-keeping followed by all the health-care sectors of Kerala. The leadership response at various levels of government was well-coordinated and prompt, and benefitted from a strong reputation built on a track record of successfully dealing with previous health emergencies[19]. As a consequence, there was a high level of cooperation from all relevant government departments as well as the well-informed population, and a high degree of adherence to the government measures, which helped implementing the model presented here. Once the model parameters were tuned to fit the data, the reference model could be run for hypothetical cases in which the various government measures had not been enacted.

The data and the model show remarkably low cases and fatalities (a total of three) till 7th May, when the lock-down was eased in districts with low case numbers and repatriation of Keralites stranded outside the state began, which has been followed by a period of exponentially growing infection, continuing into July.

Using the model to simulate what the consequences would have been, if the government had not acted promptly, leads to some sobering conclusions. According to the model simulation, in the worst case of no government action, the entire population would have become infected at some point, and the total fatality would have risen to close to two hundred thousand, within four months. No doubt, in this worst-case situation, and many of the hypothetical scenarios, Kerala's medical facilities and volunteer activities would have been over-stretched, dramatically increasing the death toll beyond what is modelled here. Note that stringent track-and-trace measures were in place from the very beginning of the outbreak in Kerala, making it difficult to evaluate the impact of this particular measure. We can only speculate that the initial $\mathcal{R}_0$ value would have been significantly higher otherwise, see for example $\mathcal{R}_0$ values greater than 3 reported from other regions[20,21].

During the period of study, the number of deaths relative to the total number of infected people was 0.7%. It has since decreased to 0.4% as of 10th July [22] though the number of cases has increased dramatically, to 6,951. The death rate is impressively low (*cf.* 2.7% for India as a whole, 15.5% for the UK, and 4.3% for the USA, according to the Johns Hopkins Coronavirus Resource Centre[1] on 10th July 2020). The role played by Kerala's public health-care system (which in itself reflects well on the foresight of multiple governments in building Kerala's health-care system over the last few decades) cannot be overlooked when analysing the low death rate in Kerala. This consideration emphasises the importance of a combination of long-term planning, as well as short-term, rapid response. No doubt other factors (such as population demographics) could have contributed to the low mortality, but they fall outside the scope of this work.

At the end of Phase-2, lock-down rules were further relaxed, leading to increased rates of infection. Hence, the measures have not succeeded in solving the problem, only delayed it. But that in itself was a major achievement for a densely-populated state such as Kerala, within a developing country. By successfully keeping the number of infected cases low in the initial four months, Kerala ensured that its medical facilities were not stretched beyond breaking point. At the end of the study period, Kerala is starting from a smaller number of infected people than many countries of comparable size, or indeed many of the other Indian states (see Table 1b and SM Figure 3), even though Kerala was the first state in India to report a case of COVID-19.

This achievement has allowed the state to (a) scale-up COVID-19 isolation and treatment facilities; (b) mobilise a massive volunteer force to help the needy; (c) put in place aid delivery mechanisms for workers who have lost their jobs and their income; and (d) inform the population of the dangers of the pandemic and of the importance of modifying social behaviour patterns to avoid community transmission. What remains unknown at present is whether the psychological pressures, brought on by the sustained threat on health, many months of social distancing, and financial hardship, could in turn lead to break down in discipline.

As government measures relax, the burden now shifts more on to the public to maintain the principles embedded in Kerala's "break the chain" campaign, for as long as the coronavirus threat remains. If the population is unable to break the chain, then the alternatives are limited: it would be either return to lock down, or head towards a major crisis, according to the model simulation.

The Kerala model highlights the importance of strong leadership in a crisis, working together with a dedicated and committed body of health-care workers and a literate and cognisant society; the value of full community engagement to fight the danger; the importance of a public health-care system that is affordable, agile and flexible; and the need for long-term commitment to building health care facilities.

The first part of the study period also demonstrates a cost-effective path that would be viable for developing societies. Now, and in the wake of the pandemic, many analyses will be undertaken to determine whether various governments took the right path to dealing with COVID-19. Several strategies will no doubt be examined. The Kerala COVID-19 response is worthy of consideration in the comparisons, not only because it flattened the curve in the early days against all odds, but also, sadly, because of the secondary period of exponential growth of cases in the subsequent, post-lock-down months.

Methods

The Kerala COVID-19 model presented here is based on the generic class of susceptible-exposed-infected-recovered (SEIR) models, with additional partitioning of the population into compartments dealing with hospitalised (h); out-of-hospital (o) and travel into state (δ). Symbols and definitions used here for all model variables are listed in Table SM-1 and for all model parameters are provided in Table SM-2. We first examine the out-of-hospital compartment.

Out-of-hospital Compartment

In the model, the rate of change in the out-of-hospital, susceptible population (S_o) is expressed as:

$$\frac{\mathrm{d}S_o}{\mathrm{d}t} = -\frac{\lambda S_o I_o}{H_o} + \omega S_h + \mu_{sp}\delta_S - \delta_T\,, \qquad (1)$$

where S_o, the out-of-hospital, susceptible compartment, decreases as some members of the pool move to the out-of-hospital, exposed compartment E_o, at the rate of ($\lambda I_o/H_o$), according to their interaction with infected, out-of-hospital people (I_o) within a total population (H_o) in the out-of-hospital pool, and the rate of transmission λ. The population S_o increases due a fraction of hospitalised susceptible population (S_h) leaving hospital, with the rate of transfer determined by ω, which is the reciprocal of the period at the end of which a person is released from hospital, if free of symptoms. The susceptible people travelling into Kerala, δ_S, who tested negative for COVID-19 also move into the S_o pool, with the rate of transfer determined by μ_{sp}, the COVID-19 test specificity. The total population is held constant through travel out of the state[23], which is assumed to be equivalent to the total population δ_T entering the state, where $\delta_T = \delta_S + \delta_E + \delta_I + \delta_R$.

The dynamics of the exposed population in the out-of-hospital compartment, E_o, are given by:

$$\frac{\mathrm{d}E_o}{\mathrm{d}t} = \frac{\lambda S_o I_o}{H_o} - pE_o + (1 - \mu_{se})\delta_E\,, \quad (2)$$

in which a part of the out-of-hospital susceptible population S_o is transferred to E_o when exposed to the disease, but prior to developing any symptoms, as represented by the term $\lambda S_o I_o / H_o$. People leave the compartment when they become infectious, moving to the out-of-hospital infected population, with this rate of transfer determined by p, the rate at which exposed people become infectious. Exposed travellers into the state who tested negative for COVID-19 (false negative) also add to the E_o pool through the term $(1 - \mu_{se})\delta_E$, where μ_{se} is the COVID-19 test sensitivity.

The rate of change in the infected, but out-of-hospital pool I_o is computed as:

$$\frac{\mathrm{d}I_o}{\mathrm{d}t} = pE_o + (1 - \mu_{se})\delta_I - rI_o - \sigma I_o, \quad (3)$$

where I_o increases when people from the out-of-hospital exposed compartment become infectious, at a rate p. The pool size also increases when travellers who do not test positive for COVID-19 enter the state ($(1 - \mu_{se})\delta_I$). This pool decreases when people recover from the disease at a rate r, the recovery rate, progressing to the out-of-hospital recovered population. The out-of-hospital infected population also decrease when members move to the hospitalised infected population when they develop symptoms identifiable as COVID-19, at a rate σ, the rate at which infected people develop noticeable symptoms.

The rate of change in the fourth pool R_o, in the out-of-hospital compartment representing the recovered population, is estimated as:

$$\frac{\mathrm{d}R_o}{\mathrm{d}t} = rI_o + \omega R_h + \mu_{sp}\delta_R\,. \quad (4)$$

The compartment R_o represents people who have had COVID-19 and recovered, and were afterwards released from hospital. This population grows when out-of- hospital infectious people recover (rI_o); when the hospitalised recovered people (R_h) are released from hospital at the rate ω, the reciprocal of the period from first negative test to release from hospital; and when recovered people travel into the state and test negative for the virus ($\mu_{sp}\delta_R$).

Hospitalised Compartment

The compartment S_h, representing hospitalised people who have not been exposed to the virus, is modelled as:

$$\frac{\mathrm{d}S_h}{\mathrm{d}t} = \left(1 - \mu_{sp}\right)\delta_S - \omega S_h\,, \quad (5)$$

in which the pool increases when travellers come into the state, and test positive for COVID-19 wrongly ($(1 - \mu_{sp})\delta_S$), and decreases when people test negative for COVID-19 and are released after a period of ($1/\omega$) days. It is assumed that hospitalised individuals are unable to contract the virus, implying a totally effective quarantine.

The hospitalised exposed population (E_h) dynamics are modelled as:

$$\frac{\mathrm{d}E_h}{\mathrm{d}t} = \mu_{\mathrm{se}}\delta_E - pE_h\,, \quad (6)$$

where increases in the compartment result from travellers into the state correctly testing positive for COVID-19 ($\mu_{se}\delta_E$) and decreases result from people becoming infectious and progressing to the hospitalised, infected, population (I_h), at rate p.

The change in the hospitalised, infected, population (I_h) is modelled as:

$$\frac{\mathrm{d}I_h}{\mathrm{d}t} = pE_h + \sigma I_o + \mu_{se}\delta_I - rI_h - D\,, \quad (7)$$

where this pool increases when the hospitalised exposed population becomes infectious (pE_h); when people in the out-of-hospital infected pool develop symptoms and are hospitalised (σI_o); and from travellers into the state correctly testing positive ($\mu_{se}\delta_I$). Population in this pool decrease with recoveries (rI_h), and from deaths (D). Deaths are modelled as occurring only in the hospitalised population, as the symptoms of COVID-19 are expected to be severe enough to be detectable prior to patient mortality.

Finally, the hospitalised recovered population (R_h) is modelled as:

$$\frac{\mathrm{d}R_h}{\mathrm{d}t} = rI_h - \omega R_h + (1 - \mu_{sp})\delta_R\,, \quad (8)$$

where increases result from recovery of hospitalised infected people (rI_h) and from entry of recovered people into the state ($(1 - \mu_{sp})\delta_R$). Decreases from people leaving hospital, having tested negative for $1/\omega$ days.

Implementation

The total number of people travelling into the state, δ_T, was modelled as an independently distributed normal random variable with mean 46,000 and standard deviation 2,000[24], until 24th March 2020, when travel into the state was restricted. After this date the number of people entering the state was greatly reduced, mainly consisting of non-resident Keralites returning to the state in repatriation efforts. The total number of cases are modelled as a uniformly-distributed random variable in the interval [0,1840] for the period after 24th March 2020 until 16th May 2020[13]. After 16th May 2020, estimates for the number of people travelling into the state are available[13], and so are used as inputs to the model.

The number of non-susceptible people travelling to the state, $\delta_T - \delta_S$, is modelled as a binomially-distributed random variable with number of trials equal to the number of people travelling into the state, and probability of success equal to the date-dependent global COVID-19 incidence rate[1]. The numbers of exposed, infected and recovered people travelling into the state (δ_E, δ_I and δ_R) are then uniformly distributed such that $\delta_T - \delta_S = \delta_E + \delta_I$

$+\delta_R$. The number of deaths were also calculated stochastically, as a binomially-distributed random variable with I_h trials, and probability d.

The actions taken by the state of Kerala led to drastic changes in transmission rates. Hence the transmission rate is modelled by the piece-wise function

$$\lambda(t) = \begin{cases} \lambda_1, & t \leq 24 \text{ March } 2020 \\ \lambda_2, & 24 \text{ March } 2020 < t \leq 20 \text{ April } 2020 \\ \lambda_3, & t > 20 \text{ April } 2020. \end{cases} \quad (9)$$

Note that Phase 2 is split into two stages on 20th April, because of the relaxations in lock-down on that day. A delay in reporting of ongoing hospitalised cases (t_d) is also fit, to reflect delays in updating of statistics due to the time required for testing, and other uncertainties. Similar delays have been fit in other COVID-19 models[25], as the novelty of the disease means testing delays affect every afflicted area.

The model is run from 30th January 2020 to 30th May 2020, assuming an initial population of 33.3 million susceptible, out-of-hospital people. Since there are stochastic components to the model (the number of people entering the state; the number of infected people; and the number of deaths per day), the model is run 30 times and the mean values for each compartment at each time point taken, such that the results presented constitute an ensemble mean.

Model assumptions

The susceptible-infected-recovered (SIR) modelling framework, of which the model above is a variation, has inherent assumptions[26,27,28]. Furthermore, there are other assumptions introduced here.

It is assumed here that the identification of people entering the state is complete, and that testing is carried out on all people entering the state. This is unlikely to be true: there are always limits to testing capacity, such that numbers entering the state above the limit cannot be tested. This could have occurred prior to the travel ban implemented on 24th March 2020. People entering the state may also go unidentified when checkpoints are avoided, or provide incomplete information on travel history.

Similarly, the model assumes that quarantining of hospitalised people is perfect, so no one in hospital interacts with those not hospitalised. In this ideal view of quarantine, there is no spread from those in hospital to those outside. However, this may not always hold, as those in hospital may come into contact with out-of-hospital people, for example through health-care workers in hospitals. Efforts have been taken in Kerala to reduce the spread in such environments, by designating entire government-run hospitals as COVID-only hospitals, and by providing essential personal protective equipment to all staff within those hospitals. Quarantining of people entering the state, and those suspected of coming into contact with infected people was an important component of the containment strategy implemented in Kerala. Within the model this is implemented implicitly, as changes in transmission rate on 24th March 2020 and 20th April 2020.

Tracking and tracing of people who came into contact with potentially infected people was also a key part of the Kerala plan. This was implemented from the very beginning of the virus's introduction into Kerala, and potentially saved many lives. In the model there is no explicit description of this, but appears as a reduction in the transmission rate λ from the outset, and changes to the value of σ, which depends on the identification of individuals with severe symptoms.

As the state enacted the track and trace system from the identified initial introduction of COVID-19, it is not possible to judge the impact the scheme has had on containment. There are no data on the disease dynamics without track and trace for the state, so no estimate on the changes to σ and λ can be estimated, and the impact of its removal is not possible to quantify with this model.

Basic Reproduction Number

The potential for a contagion to spread is often expressed as $\mathcal{R}_0$, the basic reproduction number, which represents the expected number of cases that might be infected by a single case, given all the members of the population are susceptible[20]. The $\mathcal{R}_0$ number can be computed given three of the SEIR parameters — λ, r and σ — as:

$$\mathcal{R}_0 = \frac{\lambda}{r + \sigma}. \quad (10)$$

Fitting Model Parameters

The Kerala COVID-19 model was fit using the FME package in the R programming language[29], which implements a Bayesian Monte-Carlo Markov Chain (MCMC) method. With available data on the number of active cases of COVID-19 and the number of recorded mortalities (published by the state government[13]) to fit to, we used a run-in of 1,000 steps, followed by chains of 4,000 steps to fit the set of model parameters $\{\lambda_1, \lambda_2, \lambda_3, \sigma, d, p, r, t_d\}$. The number of active cases is published daily, accounting for cases undergoing treatment in the government hospitals[13]. This includes all those who have tested positive, or display obvious, moderate to severe symptoms of COVID-19. Hence, the full hospitalised population ($S_h + E_h + I_h + R_h$) is fit to the observed number of active cases. Total mortality caused by COVID-19 is also published in daily bulletins by the government of Kerala[13]. All deaths recorded as COVID-19 have tested positive for COVID-19.

The fitted parameter values are shown in Table SM-3, along with the inferred $\mathcal{R}_0$ values, which change in the model when λ changes. The fitted model is treated as the reference model.

Hypothetical Cases Exploring Effectiveness of Government Measures

The fitted version of the model is treated as a reference. The model was then modified to explore how the various measures implemented by the Kerala government impacted the spread of COVID-19 in Kerala. Variants of the model, in which the various government measures were removed, were run from 30th January 2020 to 30th May 2020, and the number of modelled deaths due to COVID-19 in each variant case was compared against the reference model results, yielding the number of extra deaths that would have resulted, had the government not enacted the measures for reducing the spread of COVID-19.

The reference Kerala model described above combines hospitalisation and quarantine, with testing and tracing, restrictions on travel and lock-down within the state. To quantify the impact of each of these measures, they were removed individually, and in combination, and the impacts evaluated from the variant model runs.

Reduced testing

To model reduced testing of people entering the state, a testing parameter a was introduced such that the equations become:

$$\frac{\mathrm{d}S_o}{\mathrm{d}t} = -\frac{\lambda S_o I_o}{H_o} + \omega S_h + \left(a\mu_{sp} + (1-a)\right)\delta_S - \delta_T\,, \qquad (11)$$

$$\frac{\mathrm{d}E_o}{\mathrm{d}t} = \frac{\lambda S_o I_o}{H_o} - pE_o + \left(a(1-\mu_{se}) + (1-a)\right)\delta_E\,, \qquad (12)$$

$$\frac{\mathrm{d}I_o}{\mathrm{d}t} = pE_o + \left(a(1-\mu_{se}) + (1-a)\right)\delta_I - rI_o - \sigma I_o\,, \qquad (13)$$

$$\frac{\mathrm{d}R_o}{\mathrm{d}t} = rI_o + \omega R_h + \left(a\mu_{sp} + (1-a)\right)\delta_R\,, \qquad (14)$$

$$\frac{\mathrm{d}S_h}{\mathrm{d}t} = a(1-\mu_{sp})\delta_S - \omega S_h\,, \quad (15)$$

$$\frac{\mathrm{d}E_h}{\mathrm{d}t} = a\mu_{se}\delta_E - pE_h\,, \quad (16)$$

$$\frac{\mathrm{d}I_h}{\mathrm{d}t} = pE_h + \sigma I_o + a\mu_{se}\delta_I - rI_h - D\,, \quad (17)$$

and

$$\frac{\mathrm{d}R_h}{\mathrm{d}t} = rI_h - \omega R_h + a(1-\mu_{sp})\delta_R\,. \quad (18)$$

The testing rate a was 100% in the reference run and was then reduced to 10% in the hypothetical case considered here, to represent a highly inefficient testing system.

This presumes that in the reference run, the system in place is 100% effective, and that all people entering the state are tested. Note that a lower testing rate in the reference run would also change the fit, resulting in a higher value of λ and consequently a higher $\mathcal{R}_0$ number.

No travel restrictions

To represent the system with no restrictions of travel into the state, δ_T is set to pre-outbreak levels, and for the entire modelling period δ_T is treated as a normal random variable with mean 46,000 and standard deviation 2,000, with the number of non-susceptible people entering determined by the time-dependent global COVID-19 incidence[1].

Keeping δ_T at pre-outbreak levels implies there is no reduction in travel to Kerala during the outbreak. While this might have been possible, travel bans to afflicted areas had been implemented by some countries, which could have potentially reduced visitor numbers to Kerala, even in the absence of any controls on this imposed by the Kerala government. Such a reduction is not dealt within this model run.

No out-of-hospital measures

The quarantining of out-of-hospital population is treated implicitly in the reference model, with values of the transmission rate λ decreasing by 24th March, the beginning of the lock-down phase. In the variant run in which we assume there was no quarantine outside of hospital, the transmission rate λ was held constant at the pre-lock-down value λ_1.

The results of this run therefore represent the impact of no lock-down with no out-of-hospital quarantining. This presumes there was no change in behaviour of the population in response to the state interventions, and that the $\mathcal{R}_0$ number remained at 2.2 throughout the modelled period.

Another aspect of no out-of-hospital control is that no track-and-trace measures would have been implemented. It is difficult to judge what the effect of removing this measure might have been, since track-and-trace measures were implemented in Kerala from the very first day, and could have contributed to the relatively-low $\mathcal{R}_0$ value of 2.2 inferred here, compared with values between 3 and 5.7 reported for early days of COVID-19[20]. Therefore, we also carried out a simulation in which the initial $\mathcal{R}_0$ value was raised somewhat arbitrarily to 3, and the subsequent $\mathcal{R}_0$ values were increased by the same proportion (see Table SM-3). We also ran a simulation in which $\mathcal{R}_0$ of 3 was maintained throughout the simulation period, as exemplifying the case in which there was no track-and- trace, no lock-down and no out-of-hospital quarantine.

No in-hospital quarantine

To model the outcome of a COVID-19 outbreak wherein the quarantining of hospitalised individuals was ineffective, the equations were changed to allow mixing between the in-hospital and out-of-hospital populations. Hence the model equations become:

$$\frac{\mathrm{d}S_o}{\mathrm{d}t} = -\frac{\lambda S_o(I_o + I_h)}{H_o + H_h} + \omega S_h + \mu_{sp}\delta_S - \delta_T\,, \quad (19)$$

$$\frac{\mathrm{d}E_o}{\mathrm{d}t} = \frac{\lambda S_o(I_o + I_h)}{H_o + H_h} - pE_o + (1 - \mu_{se})\delta_E\,, \quad (20)$$

$$\frac{\mathrm{d}I_o}{\mathrm{d}t} = pE_o + (1 - \mu_{se})\delta_I - rI_o - \sigma I_o\,, \quad (21)$$

$$\frac{\mathrm{d}R_o}{\mathrm{d}t} = rI_o + \omega R_h + \mu_{sp}\delta_R\,, \quad (22)$$

$$\frac{\mathrm{d}S_h}{\mathrm{d}t} = \left(1 - \mu_{sp}\right)\delta_S - \omega S_h - \frac{\lambda S_h(I_o + I_h)}{H_o + H_h}, \quad (23)$$

$$\frac{\mathrm{d}E_h}{\mathrm{d}t} = \mu_{se}\delta_E - pE_h + \frac{\lambda S_h(I_o + I_h)}{H_o + H_h}, \quad (24)$$

$$\frac{\mathrm{d}I_h}{\mathrm{d}t} = pE_h + \sigma I_o + \mu_{se}\delta_I - rI_h - D\,, \quad (25)$$

and

$$\frac{\mathrm{d}R_h}{\mathrm{d}t} = rI_h - \omega R_h + \left(1 - \mu_{sp}\right)\delta_R\,. \quad (26)$$

In this set of simulations, we explore theoretically the effect of complete break-down in the quarantine of hospitalised population. This hypothetical case could occur if the hospital staff were not wearing appropriate personal protective equipment, or insufficient safety procedures were put in place for workers and non-COVID-19 patients.

All measures removed

The final variation considers an outbreak where no action was taken by the state of Kerala to prevent the spread of the disease. This is modelled by combining the variant implementations above, such that the model equations become

$$\frac{\mathrm{d}S_o}{\mathrm{d}t} = -\frac{\lambda S_o(I_o + I_h)}{H_o + H_h} + \omega S_h + \left(a\mu_{sp} + (1 - a)\right)\delta_S - \delta_T\,, \quad (27)$$

$$\frac{\mathrm{d}E_o}{\mathrm{d}t} = \frac{\lambda S_o(I_o + I_h)}{H_o + H_h} - pE_o + \left(a(1 - \mu_{se}) + (1 - a)\right)\delta_E\,, \quad (28)$$

$$\frac{\mathrm{d}I_o}{\mathrm{d}t} = pE_o + \big(a(1-\mu_{se}) + (1-a)\big)\delta_I - rI_o - \sigma I_o\,, \quad (29)$$

$$\frac{\mathrm{d}R_o}{\mathrm{d}t} = rI_o + \omega R_h + \Big(a\mu_{sp} + (1-a)\Big)\,\delta_R\,, \quad (30)$$

$$\frac{\mathrm{d}S_h}{\mathrm{d}t} = a\big(1-\mu_{sp}\big)\delta_S - \omega S_h - \frac{\lambda S_h (I_o + I_h)}{H_o + H_h}\,, \quad (31)$$

$$\frac{\mathrm{d}E_h}{\mathrm{d}t} = a\mu_{se}\delta_E - pE_h + \frac{\lambda S_h (I_o + I_h)}{H_o + H_h}\,, \quad (32)$$

$$\frac{\mathrm{d}I_h}{\mathrm{d}t} = pE_h + \sigma I_o + a\mu_{se}\delta_I - rI_h - D\,, \quad (33)$$

and

$$\frac{\mathrm{d}R_h}{\mathrm{d}t} = rI_h - \omega R_h + a\big(1-\mu_{sp}\big)\delta_R\,. \quad (34)$$

The transmission rate λ is kept constant at λ_1, throughout the run, and the travel into the state is kept at pre-lock-down levels. The testing rate *a* is set to 0%, representing no efforts to test the population. The model now presumes full mixing within the population.

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Tables

Table 1: Observations and Model Results

(a) Kerala Observations and Model Results						
	Total Cases		Reported cases			
Model	Maximum	Cumulative	Maximum	Cumulative	Deaths	Mortality (%)
Observed	-	-	624	1208	9	0.75
Reference model	1,216	2,461	527	1,273	7	0.55
Reduced Testing	7,429	14,945	3,148	7,602	38	0.50
No travel restrictions	5,513	9,307	2,496	4,326	19	0.44
No out-of-hospital measures	2,929,445	4,532,694	1,297,735	1,858,905	7,325	0.39
No in-hospital quarantine	8,715,923	33,275,191	7,897,775	28,609,435	178,929	0.63
All measures removed	16,647,096	33,300,143	14,937,074	28,669,034	188,378	0.66
No track and trace	750,502	1,025,938	214,711	284,957	1,154	0.41
No track and trace, no out-of-hospital measures	14,244,068	32,556,675	12,889,305	27,737,858	152,385	0.55
(b) Data, for a subset of afflicted countries, for comparison						
Country			Active	Cumulative	Deaths	Mortality (%)
Canada 35.2 M			35,992	91,667	7,158	7.8
Egypt 100 M			16,843	23,449	913	3.9
Germany 83 M			9,751	183,189	8,530	4.7
Italy 60 M			43,691	232,664	33,340	14.3
India			89,706	181,827	5,185	2.9

1,380 M						
New Zealand 4.8 M			1	1,504	22	1.5

Table Legend: (a) Observations and results from the reference model run, along with runs varying the level of state intervention. Mortality is calculated as the ratio of deaths to cumulative hospitalised cases. (b) Observations from other regions and countries, for comparison. All snapshots are for 30th May, 2020. For the countries, the total population is given below the names, in units of millions (M). Timeseries for these countries are shown in figure SM-3.

Figures:

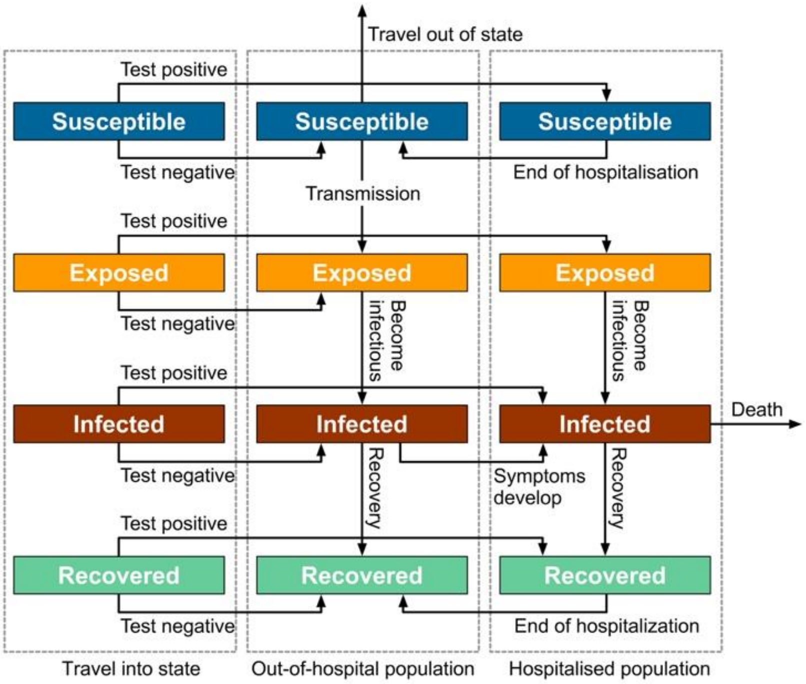

Figure 1 legend: Kerala model structure. See methods section for details.

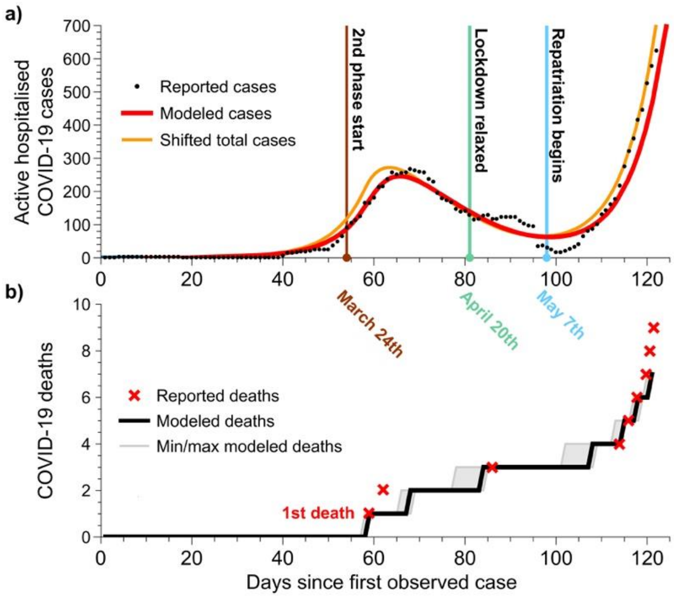

Figure 2 legend: Observed and modelled COVID-19 cases in Kerala, from January 30th to May 30th 2020. (a) Modelled and reported active, hospitalised COVID-19 cases in the state. Also shown is the modelled total cases (in and out of hospital combined), shifted by 5 days, which is the number of days in the model between someone being suspected of having the disease and being officially reported. (b) Modelled and observed cumulative deaths due to COVID-19 in Kerala.

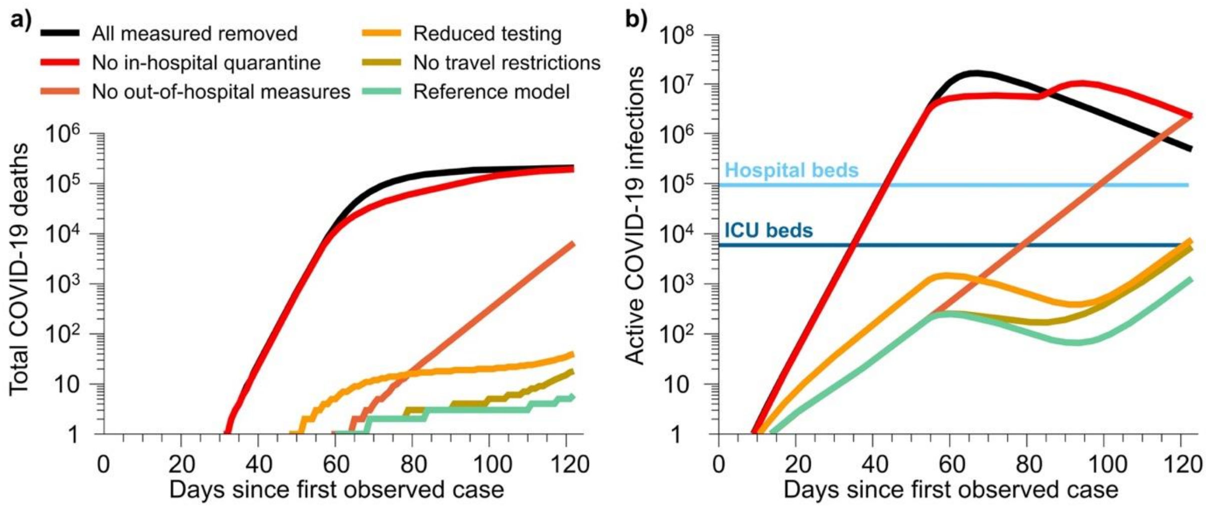

Figure 3 legend: Results from the exploration of government measures. (a) Compares the deaths due to COVID-19 in the state, and (b) compares the active COVID- 19 cases in Kerala. The number of hospital beds and ICU beds available in Kerala are also shown.

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Author Contributions

EG provided the model and calculations.

The manuscript was written with contributions from all authors.

EG, SS, ŽK and CEK prepared the figures.

Experiment design was produced by EG, SS and TP.

Competing Interest statement

The authors declare no competing interests.

Data Availability and Code Availability statement

Code is available from the corresponding author on request.

Extended Data

Methods Table SM-1: Notation in the Kerala model

Notation	Definition	Unit
δ_E	Exposed people who travel into the state.	day^{-1}
δ_I	Infected people who travel into the state.	day^{-1}
δ_R	Recovered, immune people who travel into the state.	day^{-1}
δ_S	Susceptible people who travel into the state.	day^{-1}
δ_T	Total people travelling into the state.	day^{-1}
D	Deaths.	day^{-1}
E_h	Hospitalised exposed population.	-
E_o	Out-of-hospital exposed population.	-
H_h	Total hospitalised population.	-
H_o	Total out-of-hospital population.	-
I_h	Infected hospitalised population.	-
I_o	Infected out-of-hospital population.	-
R_h	Recovered hospitalised population.	-
R_o	Recovered out-of-hospital population.	-
S_h	Susceptible hospitalised population	-
S_o	Susceptible out-of-hospital population.	-

Table legend: Variables and definitions included in the Kerala COVID-19 model, and the model variants.

Methods Table SM-2: Parameters in the Kerala model.

Parameter	Definition	Value	Unit
λ	Transmission rate.	Fitted	day^{-1}
μ_{se}	COVID-19 test sensitivity.	0.85[15]	-
μ_{sp}	COVID-19 test specificity.	1[15]	-
σ	Proportion of infected people who develop noticeable symptoms.	Fitted	day^{-1}
ω	Reciprocal of period from first negative test to release from hospital.	1[13]	day^{-1}
d	Probability of death for hospitalised infected people.	Fitted	day^{-1}
p	Rate at which exposed people become infectious.	Fitted	day^{-1}
r	Recovery rate.	Fitted	day^{-1}
t_d	Delay in reporting of hospitalised cases.	Fitted	days

Table legend: Parameters included in the Kerala COVID-19 model. Assigned parameter values, from literature are given here. Fitted parameters are displayed in Table 3.

Methods Table SM-3: Fitted parameter values

Parameter	Fitted value	95% Confidence interval	Inferred $\mathcal{R}_0$
λ_1	1.1	(1.1, 1.1)	2.2
λ_2	0.11	(0.11, 0.11)	0.21
λ_3	1.1	(1.1, 1.1)	2.1
σ	0.44	(0.44, 0.44)	
d	0.00048	(0.00048, 0.00048)	
p	0.2	(0.2, 0.2)	
r	0.071	(0.071, 0.071)	
t_d	5.0	(5.0, 5.0)	

Table legend: Fitted values of parameters. Note that the $\mathcal{R}_0$ value changes in the model with transmission rate, λ, but is also dependent on the values of r and σ.

Figure SM-1:

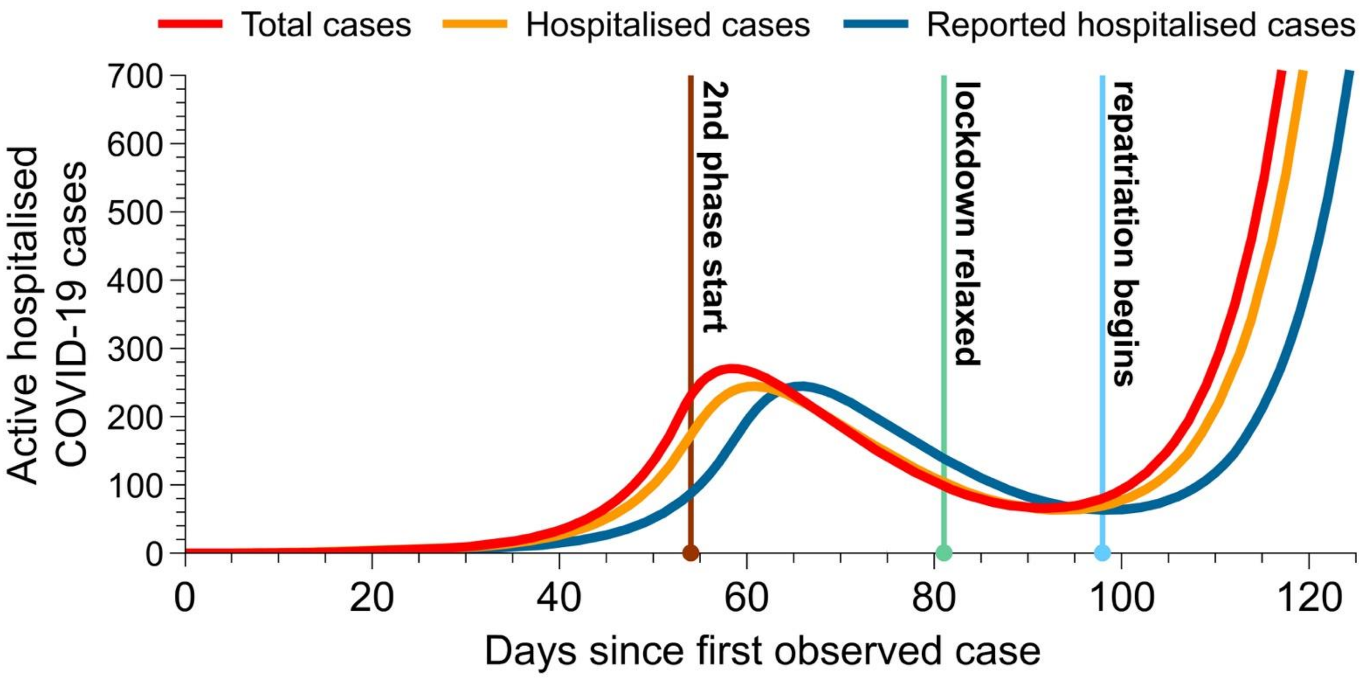

Figure legend: Comparison of total cases, hospitalisations and reported hospitalisations output by the model. Prior to day 90 the state had manged to contain all cases in hospitals.

Figure SM-2:

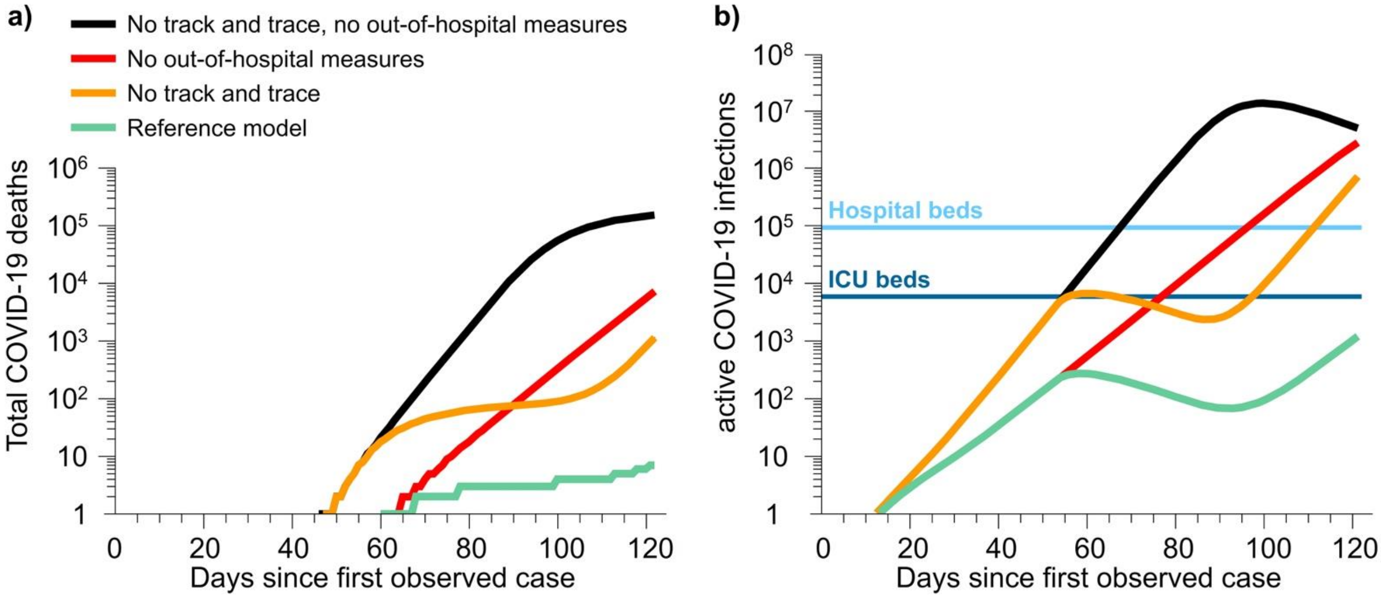

Figure legend: Comparing the model under different levels of action, with $\mathcal{R}_0$ set to 3 to reflect a scenario with no track and trace implemented.

Figure SM-3:

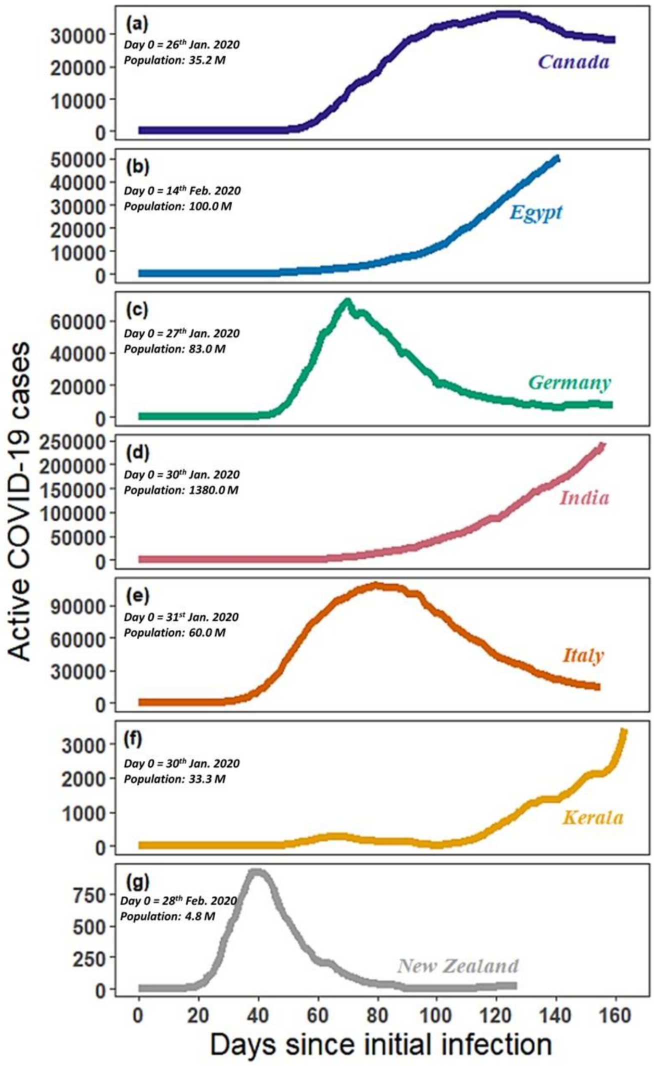

Figure legend: Comparing the Kerala timeseries of active cases of COVID-19 with selected countries.

Figures

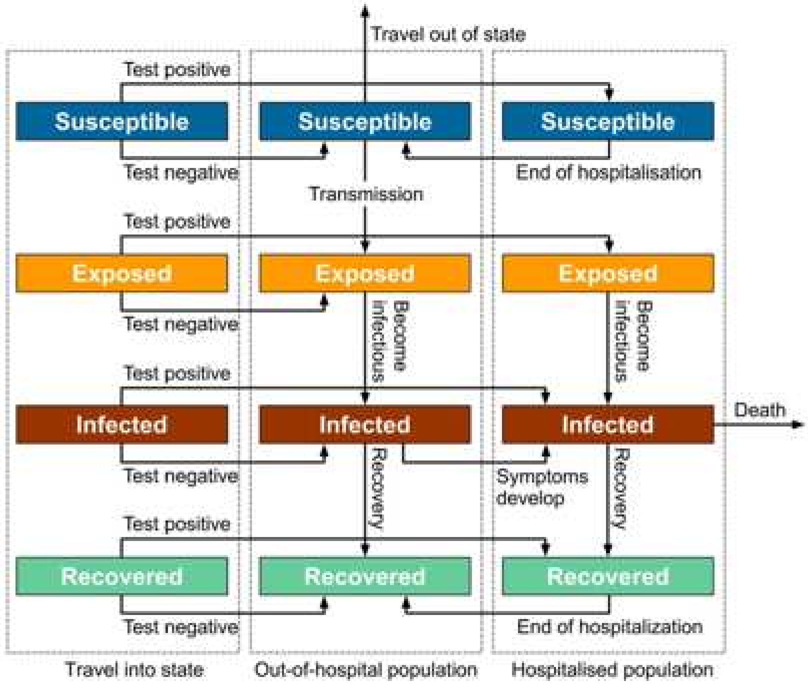

Figure 1

Kerala model structure. See methods section for details.

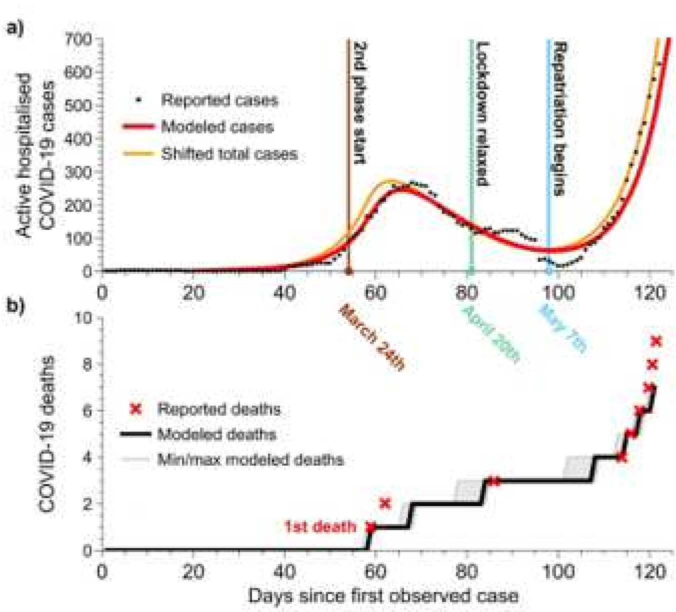

Figure 2

Observed and modelled COVID-19 cases in Kerala, from January 30th to May 30th 2020. (a) Modelled and reported active, hospitalised COVID-19 cases in the state. Also shown is the modelled total cases (in and out of hospital combined), shifted by 5 days, which is the number of days in the model between someone being suspected of having the disease and being officially reported. (b) Modelled and observed cumulative deaths due to COVID-19 in Kerala.

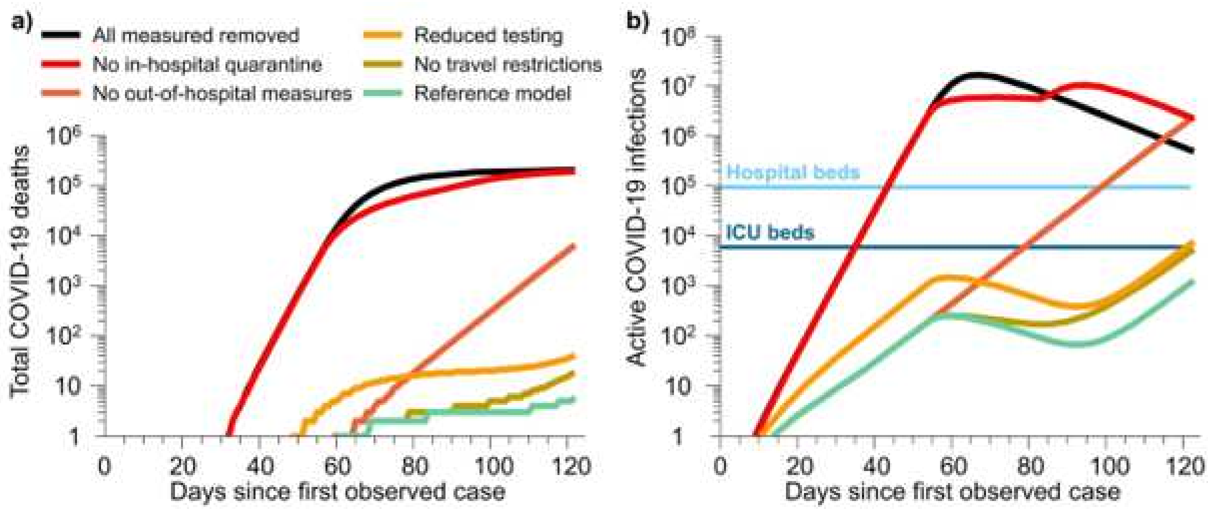

Figure 3

Results from the exploration of government measures. (a) Compares the deaths due to COVID-19 in the state, and (b) compares the active COVID- 19 cases in Kerala. The number of hospital beds and ICU beds available in Kerala are also shown.