COVID-19 Case Prediction and Outbreak Control of Navy Cluster in Sri Lanka: Effectiveness of SIR Model

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Keywords: COVID-19, SIR Model, Navy Cluster, Outbreak Management

Posted Date: December 30th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-70722/v2

Abstract

Introduction: Infectious diseases such as coronavirus disease 2019 (COVID-19) can spread contagiously fast in semi-confined places, which demand prompt public health interventions such as isolation and quarantine for their effective control. An outbreak of COVID-19 was reported within a cluster of Navy personnel in the Western Province of Sri Lanka commencing from 22nd April 2020. In response, an aggressive outbreak management program was launched by the Epidemiology Unit of the Ministry of Health supported by the Sri Lanka Navy. The objective of this research was to predict possible number of cases within the susceptible population in Sri Lanka Navy.

Methods: COVID-19 Hospital Impact Model for Epidemics (CHIME) developed by Predictive Health Care Team at Penn Medicine, Philadelphia, USA, which was a Susceptibility, Infected and Removed (SIR) model was used. The model was run on 20.05.2020 for a susceptible population of 10400, with number of hospitalized patients on the day of running the model being 357, first case hospitalized on 22.04.2020 and social distancing being implemented on 26.04.2020. Social distancing scenarios of 0, 25, 50 and 74% were run with 10 days of infectious period and 30 days of projection period.

Results: With increasing social distancing measures, the peak number of infected persons decreased, and the duration of the curve extended. With increasing social distancing from 0% to 74%, the date on which the peak number of infected cases was reported increased from 49th day to the 54th day, the doubling time increased from 3.1 days to 4.1 days, the Ro decreased from 3.54 to 2.83, and expected daily growth rate decreased from 25.38% to 18.53%. The number of COVID-19 cases prevented as per the model ranged from 2.3 – 21.1 %, compared to the base line prediction of no social distancing. When comparing the observed number of cases with the baseline model with no social distancing, a 90.3% reduction was observed.

Conclusion: The research demonstrated the practical use of a prediction model made readily available through an online open-source platform for the operational aspects of controlling outbreaks such as COVID-19 in a closed community. Predictive modelling is a useful tool for outbreak management.

Introduction

While security forces are essential to stay in such confined places as per their operational requirements, spread of COVID-19 could have serious repercussions not only on the staff of the forces, but also on national security. Sri Lanka being an island nation, the role played by Sri Lanka Navy is pivotal, especially in a scenario of high transmission rates in the neighboring countries. On 22ndof April 2020, a new case from Polonnaruwa district, a navy sailor attached to the Sri Lanka Navy Base at Welisara, who was on leave tested positive for COVID-19(4).Subsequently increasing number of COVID-19 cases were diagnosed from the same Naval Base. Having confirmed an outbreak in the Naval Base, several public health measures were implemented by the Sri Lanka Navy and together with the Epidemiology Unit of the Ministry of Health based on the findings of epidemiological investigations.

It was necessary to predict how the outbreak could spread among the confined space of the Navy base, in order to understand the health system demand from the infected individuals, as well as to quantify the effects on operational continuity of the Navy. The objective of this exercise was to predict possible number of cases within the susceptible population in Sri Lanka Navy Base at Welisara and their associated operational units in the Western Province, to be used primarily for operational planning purposes by the Ministry of Health to control a possible outbreak of COVID-19 in Sri Lanka. The specific objectives of the study were to predict the number of COVID-19 cases among the exposed population under suggested different social distancing scenarios and to compare the actual number of cases reported with those predicted by the model based on the preventive measures implemented by the Epidemiology Unit, Ministry of Health, Sri Lanka Navy, and Ministry of Defense as a collaborative effort.

Methodology

Mathematical models could be a key tool in response to outbreaks such as COVID-19(5–7). Susceptibility, Infected and Removed (SIR) Model is one of the simplest compartmental models, and many models are derivatives of this basic form(8–12).Nesteruk used this popular SIR model to get optimal values for the model parameters with the use of statistical approach(13). The SIR model has been widely used by many in modelling disease control activities among others(14,15).

As described by Kermack and McKendrick, the SIR model consists of three compartments: **S** for the number of **s**usceptible, **I** for the number of **i**nfectious, and **R** for the number of removed (**r**ecovered and thus immune or deceased) individuals) of which the relationship is explained below (8).

- N = total population
- N = S+I+R
- ß = the average number of contacts per person per time
- γ = Number of infected individuals
- t = time
- d = differential

$$\frac{dS}{dt} = -\beta SI$$

$$\frac{dI}{dt} = \beta SI - \gamma I$$

$$\frac{dR}{dt} = \gamma I$$

As per the SIR model shown in Figure 1, the population can be seen as confined to three compartments, susceptible, infected or recovered. An individual may move between compartment as the disease continues to spread in the community, however, at a given time, one person could be only in one of the three compartments(16).

The number of susceptible persons will gradually decrease as the number of infected persons gradually rise, peak and decline. Parallel to that, the number of recovered persons will gradually increase. It is only applicable during the period prior to a region's peak infections, and it accounts only for a single significant social distancing policy. COVID-19 Hospital Impact Model for Epidemics (CHIME) developed by Predictive Health Care Team at Penn Medicine, Philadelphia, USA, uses a Monte Carlo simulation instantiation of a susceptible, infected, removed (SIR) model with a 1-day cycle (17). The CHIME model is used to predict hospital capacity needs during COVID-19 using local model inputs, which has an easy to use public web (17). We chose the CHIME model since it was simple and ready to be deployed even by busy and on the job outbreak response teams.

The CHIME model is specifically developed to assess hospital capacity needs during COVID-19. In the Sri Lankan context, we had to rethink some of the model inputs. In the CHIME model, hospital market share needs to be provided. In Sri Lanka, all patients who are diagnosed with COVID-19 are centrally and dynamically allocated case-by case to a designated hospital. These designated state-owned hospitals are providing services free of charge and do not have rigid catchment area boundaries. Hence, we projected the model to the whole of the hospital system of Sri Lanka which could be used for admitted COVID-19 confirmed persons. Hence, both hospital market share and percentage of hospital admissions were kept as 100%. Further, epidemiological pattern from the time of onset of the outbreak to the point of running the CHIME model has shown that most of the COVID-19 patients were healthy and asymptomatic Navy personnel. Hence, it was decided that there was no requirement for modelling in Intensive Care Unit admissions and ventilated proportions during the current exercise.

The Navy cluster discussed in this paper emerged around the Naval Base Welisara which is located 10 km inland in the Gampaha district of the Western Province of Sri Lanka. It belongs to the Western Naval Area of Sri Lanka Navy. Welisara Naval Base is a complex that hosts all ranks of navy personnel, office buildings, a recruitment center, a training center, a hospital, apparel facility, living quarters and a welfare center. It comprises of a susceptible population of 10,400 persons including family members of the Navy personnel.

We ran the model on 20.05.2020 using the following model inputs given in Table 1:

Table 1: CHIME Model Inputs forCOVID-19 Outbreak of the Navy Cluster in Sri Lanka

Description	Measure	Source
Susceptible population	10400	Sri Lanka Navy
No. of hospitalized as per 2020.05.20	357	Epidemiological Unit
First case hospitalized	22.04.2020	Epidemiological Unit
Social distancing implemented from	26.04.2020	Epidemiological Unit
Social distance%	0%, 25%, 50% and 74%*	
Infectious days	10	
Projected days	30	CHIME Model

* Highest social distancing percentage that the web-interphase provided (74%) was used.

The excel files generated through the CHIME model was analyzed using IBM SPSS Statistics 21 to prepare the diagrams.

It should be noted that the susceptible population of 10400 persons consisted of Navy personnel as well as their close family contacts of them. In addition, we plotted the daily number of cases from the Sri Lanka Navy Cluster as reported daily in the Daily Situational Report issued by the Epidemiological Unit.

It should also be noted that some of the preventive measures were commenced as early as 23.04.2020, however, for the modelling purposes, the date from which the full-scale social distancing commenced was taken as 26.04.2020.

Results

The SIR models under different social distancing scenarios obtained through the CHIME model are presented in figure 2. In addition, the peak number of infected cases under different social distancing scenarios as well as the day of the peak number of cases under different social distancing scenarios were compared as shown in Table 2.

Table 2: Day and Peak Number of Infected Cases: Predicted and Observed

Social distancing	Day of Peak Number of Infected Cases from first case	Peak Number of Infected Cases
0%	49	3658
25%	49	3479
50%	51	3180
74%	54	2555

As per Figure 2 and table 2, it is evident that with increasing social distancing measure, the peak number of infected persons decreases, as well as the duration of the curve prolongs. The day of peak number of

infected cases from the first case ranged from 49th day to 54thday under social distancing scenarios from 0% to 74%. The peak number of infected cases varied from 3658to 2555. The doubling time R_0 and growth rate under different social distancing scenarios are shown in Table 3.

Table 3: Doubling time, Ro and Daily Growth Rate under

Different Social Distancing Scenarios

Model	Doubling time (days)	Ro	Daily growth rate
No social distancing	3.1	3.54	25.38%
25% social distancing	3.3	3.36	25.58%
50% social distancing	3.7	3.07	20.70%
74% social distancing	4.1	2.83	18.33%

As per table 3, it is evident that doubling time increased from 3.1 days to 4.1 days from no social distancing to application of 74% social distancing. Corresponding to this, Ro has decreased from 3.54 to 2.83. Expected daily growth rate of COVID-19 cases also decreased from 25.38% to 18.53% under the application of afore mentioned increasing social distancing scenarios.

Next, we plotted the number of daily COVID-19 cases as projected under different social distancing scenarios for the susceptible Navy population along with the observed or actually reported number of COVID-19 cases on a daily basis in line with the outbreak control measures. This was intended to examine how the epidemiological curves of projected and observed or actually reported cases would relate to each other (Figure 3).

As per figure 3, it could be seen that the observed or actually reported number of cases were well above the projected number of cases up to 07.05.2020. However, beyond this date the reported number of cases were lower than the projected number of cases from the model under four social distancing scenarios considered. The typical bell-shaped epidemiological curve was not observed among the observed or the actual COVID-19 cases. Next, we plotted the cumulative number of cases predicted by different social distancing scenarios along with the observed cumulative number of cases among the Navy cluster cases.

As per Figure 4, the cumulative number of observed cases was overriding the cumulative number of projected cases from the model till20.05.2020. Then, it continued at a very low intensity until the end of the modelling period. A steady decrease in the peak of projected curves is seen with the application of increasing social distancing levels.

Table 4 : Number of COVID-19 Predicted or Observed and Prevented among the Navy cluster Population

Scenario	Number of Cases	Number of cases prevented compared to no social distancing	Percentage reduction of cases compared to no social distancing
Prediction: No Social distancing	9431	N/A	N/A
Prediction: 25% Social distancing	9209	222	2.3
Prediction: 50% Social distancing	8743	688	7.9
Prediction: 74% Social distancing	7435	1996	21.1
Observed	906	8525	90.3

Key - N/A; Not applicable.

As per the table 4, it is seen that the number of COVID-19 cases prevented as per the model ranged from 2.3 – 21.1 %compared to the base line prediction of no social distancing. However, based on the observed number of cases and the baseline model with no social distancing, it is evident that 8525 cases have been prevented which accounts for 90.3% reduction up to the end of the modelling period.

Discussion

COVID-19 is a Public Health Emergency of International Concern (18)for which the Sri Lankan health sector proactively and timely implemented action, based on the already existing National Influenza Pandemic Preparedness Plan(19). The country mobilized all relevant stakeholders under the readiness of responding to emergencies under the International Health Regulations core capacity development(20). The assistance from the security forces was received to complement the work by the health sector in curtailing the COVID-19outbreak.Prior to the emergence of the Navy cluster, there were several other clusters of COVID-19 patients which were successfully managed in Sri Lanka. However, the Navy cluster was quite unique. Firstly, it marked the occurrence of the largest number of cases within a confined population. Secondly, if the COVID-19 cluster within the Navy personnel was not successfully managed, it would have led to the paralysis of the functional capacity of the Sri Lanka Navy. This would have had serious repercussions on border security concerns, as an island nation.

The Epidemiology Unit in collaboration with the Sri Lanka Navy conducted a detailed epidemiological investigation on the outbreak in the Navy cluster experienced in the Sri Lanka Navy Base at Welisara and

their associated operational units. However, as per the preliminary investigations, a susceptible population of10400Navy personnel were identified and considered for the running of the model. As a part of the operational response, the SIR model was used to predict the probable number of infected persons amongst the Navy Cluster.

Under the (0) social distancing scenario, the daily case load was predicted to peak up to 3658cases on the49thday. Further, under the best predictable social distancing scenario (74%), the number of daily cases would peak to 2555 on the 54thday. The network of designated hospitals and preventive health services were ready to anticipate and receive a large influx of COVID-19confirmed cases from the Sri Lanka Navy based on this case prediction scenario. A series of COVID-19treatment hospitals with increasing bed capacity were identified as a response activity. However, country was able to control this outbreak situation in a very effective manner, implementing different preventive strategies, in addition to the social distancing, probably accounting to more stringent than even 74%.

It was also found that the observed number of daily cases and observed cumulative number of cases seems to be much higher at the initial stages of the outbreak than the predicted number of daily cases and the predicted cumulative number of cases. This may signal the dangerous levels that the outbreak would have escalated into, if successful control measures were not implemented. However, subsequently, both the projected number of daily cases and the cumulative number of cases became lower than the reported number of daily cases and the cumulative number of reported cases.

More ever, the predicted number of COVID-19 cases within the Navy Cluster based on all four different social distancing scenarios were much higher than the actual number observed. When comparing the proportion of cases prevented in relation to the no social distancing scenario, 2.3%, 7.9% and 21.1% were prevented by 25%, 50% and 74% social distancing scenarios. However, when comparing the proportion of actual number of cases prevented compared to the no social distancing scenario, the prevented percentage rose to 90.3.

One possible reason for the large gap between the predicted and actual number of cases observed could at least be partly attributed to the assumptions on which SIR model is based on. The SIR model assumes a fully connected population, where there is homogeneous mixing of infected and susceptible population(21). If the afore mentioned mixing falls anything less than 100%, the mode will have a bias of overestimating the number of cases that will arise. Hence, during the scenario under study among the Naval personnel, one reason why the model provided overestimates could be that the level of mixing in the actual population was less than the model assumed to be.

In addition, the observed significant reduction of cases could be attributed to cumulative effect of multiple, timely and rigorous outbreak control measures including social distancing implemented by the Ministry of Health and the Sri Lanka Navy. In order to reduce the congestion within the camps, susceptible population was redistributed to a series of designated centers under strict quarantine procedure. In the meantime, the close contacts including family members of the Navy personnel who

returned home from the Naval base were sent for institutional quarantine. Further, testing of all susceptible individuals was carried out for COVID-19. The other forces supported the Sri Lanka Navy to collaboratively work on institutional quarantining together with public health authorities to institute relevant preventive measures on timely basis.

COVID-19 patients were identified and isolated irrespective of them being symptomatic or not. Firstly, this indicates that the number would have been lower, if only symptomatic patients were accounted for. This actually has contributed to an overestimating of the observed number of COVID-19 patients. Secondly, similar strict preventive health measures were implemented in a uniform manner irrespective of the positively diagnosed COVID-19 patients being symptomatic or not, despite contrasting evidence on infectivity of asymptomatic COVID-19 positive patients (22–25). This highlights again the effects of stringent preventive health measures that contributed to the outbreak control.

Further, the predicted Ro under different social distancing scenarios during the current study ranged from 3.54, 3.36, 3.07 and 2.83 under 0%, 25%, 50% and 74% social distancing scenarios. Such effect by social distancing on the control of the spread of the diseases has been shown elsewhere in the world. For example, a large number of COVID-19 cases have been prevented due to rigorous preventive health measures in the aircraft carrier USS Theodore Roosevelt which arrived in Guam in March 2020, which had a similar semi-confined population (2). In the meantime, the R_0 in the Diamond Princess Cruise Ship was to be 4 times higher than to theR_0in Wuhan. As per the modelling, it was found that the initial R_0 of 14.8 which reduced to 1.78 with the isolation and quarantine measures(3).

When considering the observed daily reported case trend of the Sri Lanka Navy Cluster, the typical bell-shaped epidemiological curve was not seen. This again could explain the vigorous interventions carried out to curtail the outbreak.

The SIR is one is the simplest mathematical models which makes it easy to use. The CHIME model with its web application has made it further simple and ready to “plug and play” even by busy and on the job outbreak response teams. The SIR model could be effectively used to predict infectious disease outbreaks in semi-confined populations such as Cruise Ships, Military Barracks, and College Dormitories elsewhere. Such settings easily fulfil the assumptions required for the application of the SIR model, namely a connected population where the homogenous mixing of infected and susceptible population occurs. One possible disadvantage of the same model, especially applied, to a non-confined population would be over estimation of the case numbers due to lack of homogeneous mixing of infected and susceptible individuals. For example, the model would over estimate the number of cases when applied to a region or a country, where the mixing of infected and susceptible populations will not be that good.

Conclusions

This exercise demonstrated the practical use of a prediction model made readily available through an online open-source platform for the operational aspects of controlling a COVID-19 outbreak or similar

communicable disease outbreaks in a closed community such as armed forces. At the initial stages, the results of predictions could be used for understanding the magnitude of the outbreak in the Sri Lanka Navy Cluster that the country was yet to encounter.

In addition, such findings could be used for strategic planning for curtailing the outbreak and for health system preparedness. Further, lessons from such prediction modelling could be used for forecasting existing or new infectious diseases in future. While active epidemiological surveillance, contact tracing, case isolation and case management should be the cornerstone of outbreak management, epidemiological modelling could supplement above efforts.

List Of Abbreviations

COVID-19	Coronavirus Disease 2019
SIR	Susceptible, Infected and Removed
CHIME	COVID-19 Hospital Impact Model for Epidemics
Ro	Basic Reproduction Rate

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Funding

Not applicable

Authors' contributions

N.W.A.N.Y.W developed the research methodology, planned and managed the overall research. NH conducted an in-depth analysis of the use of SIR model and along with KALCK did the running of the model. TR, MK, AH collected and collated the reported cases of COVID-19 from Sri Lanka Navy Cluster. H.D.B. H, SJ, TR, MK, SS, SG, and DG contributed methodological and epidemiological improvements. DG has overseen the scientific vigour and quality assurance at all stages. All authors read and approved the final manuscript.

Acknowledgements

Not applicable

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AH and SR are attached to the Sri Lanka Navy.

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Figures

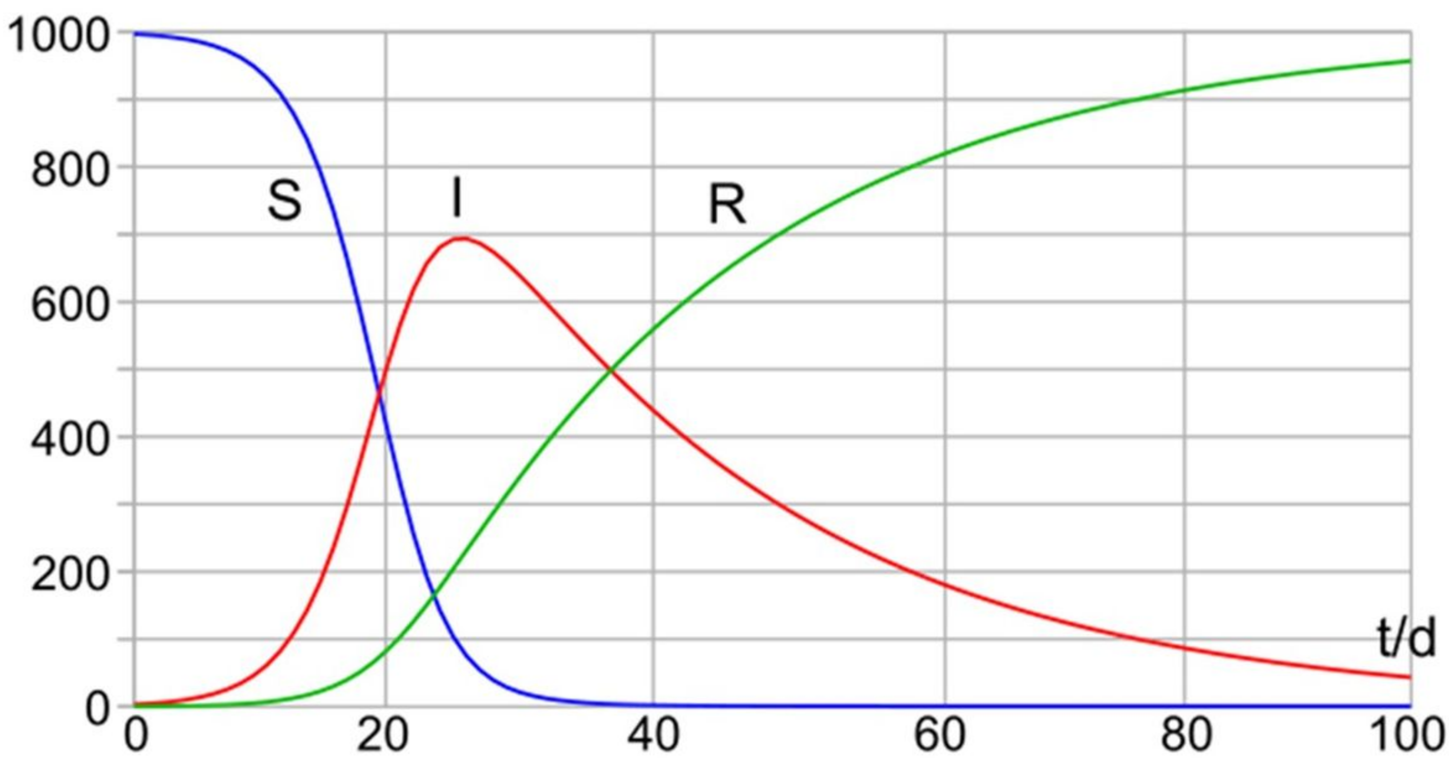

Figure 1

SIR Model: S = Susceptible, I = Infected, R = Removed; Blue line indicates the fate of the susceptible population. The hypothetical susceptible population of 100 gradually decreases. The red line shows the curve of the infected. The number infected peaks around 25th day and then gradually decreases. The blue line shows the removed individuals, who are either recovered or dead following the infection. It

should be noted that at a given time, the sum of the susceptible, infected and removed are equal to the total susceptible population at the commencement modelling period.

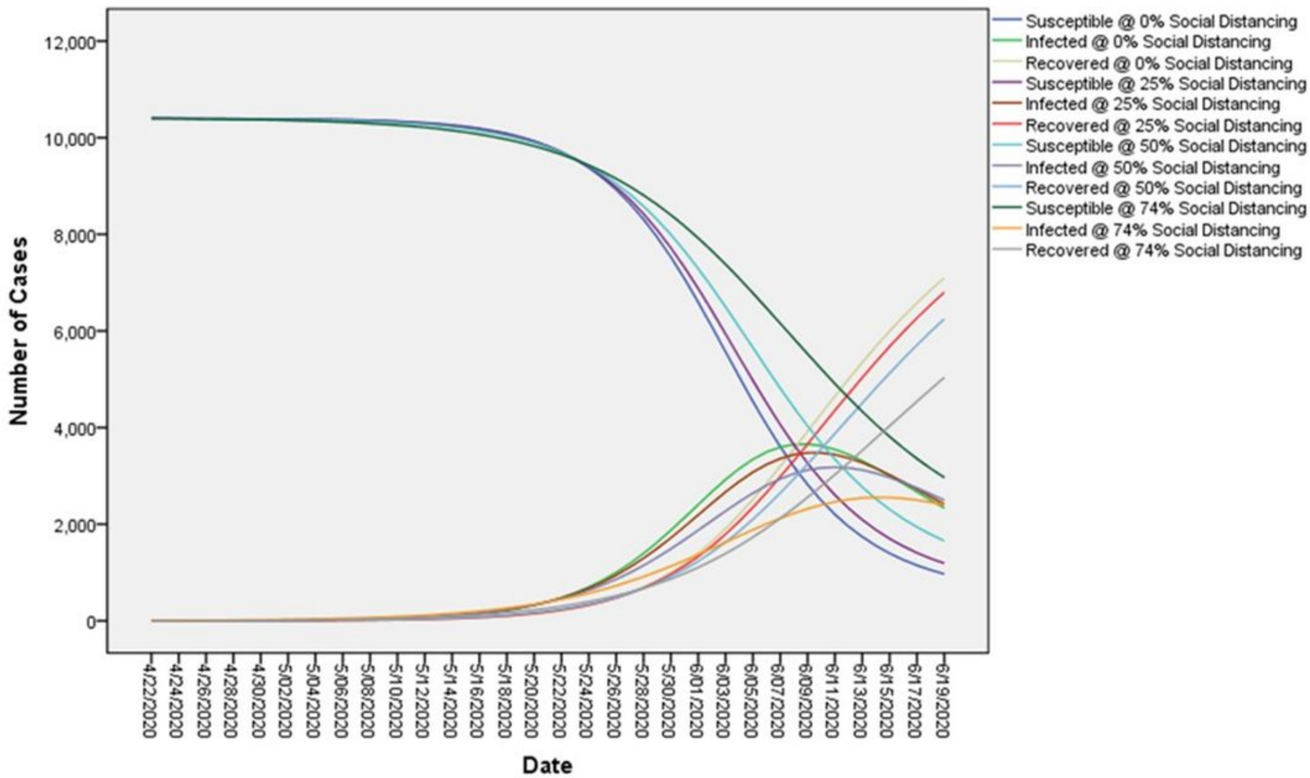

Figure 2

SIR Model for Different Social Distancing Scenarios: S = Susceptible, I = Infected, R = Removed; Susceptible, Infected and Removed curves for 0%, 25%, 50% and 74% social distancing scenarios are shown in 12 colored lines. The peak of the infected curve flattens and delays with increasing social distancing scenarios, along with comparable changes seen in susceptible and recovered curves.

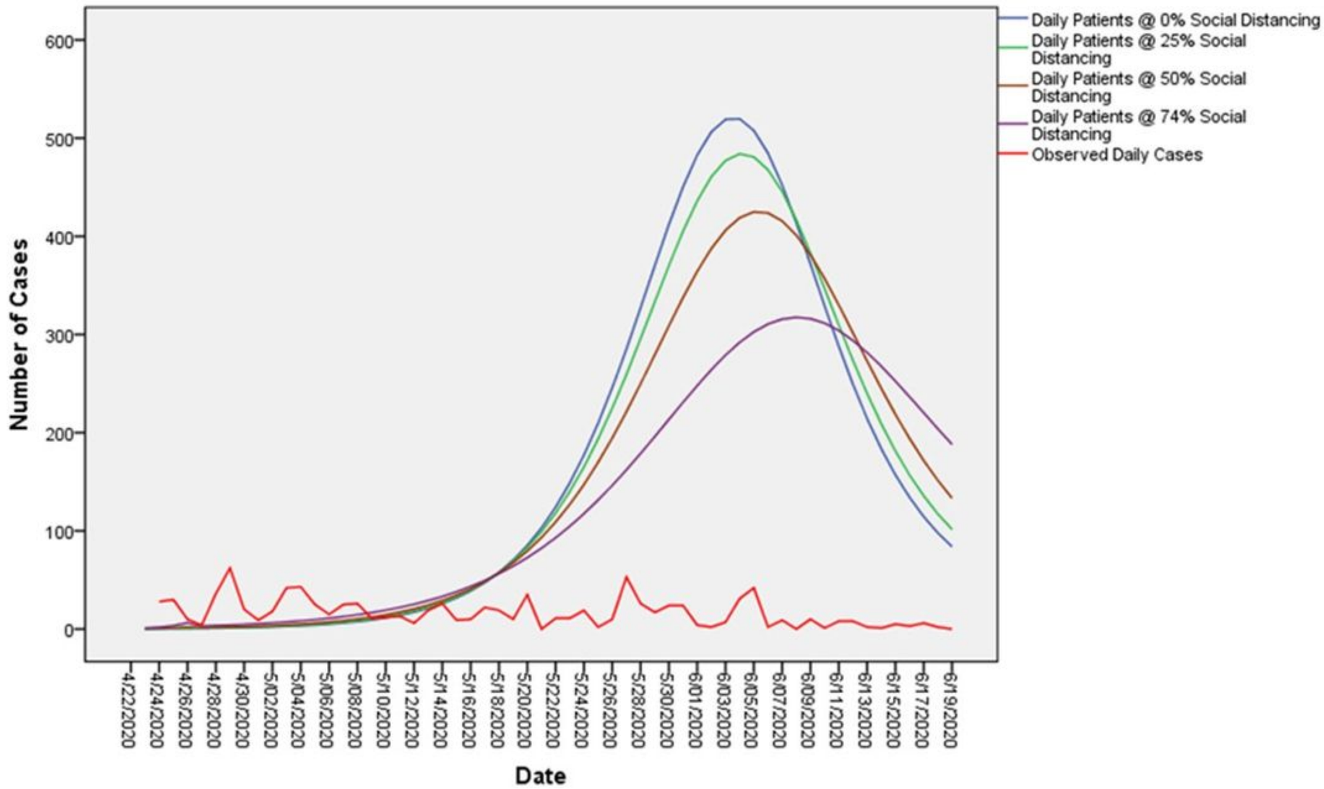

Figure 3

Projected and Observed Daily Cases: The projected daily patients under 0%, 25%, 50% and 74% social distancing scenarios are shown in blue, green, brown and purple lines respectively. The projected daily patient curve flattens with increasing social distancing scenarios, while the time to the peak prolongs. The red line shows the observed daily cases which continue to be above the projected daily patient lines of all four social distancing scenarios up to 07.05.2020. However, since this date, the red line showing the observed number of cases curve goes below the projected number of cases under four social distancing scenarios considered.

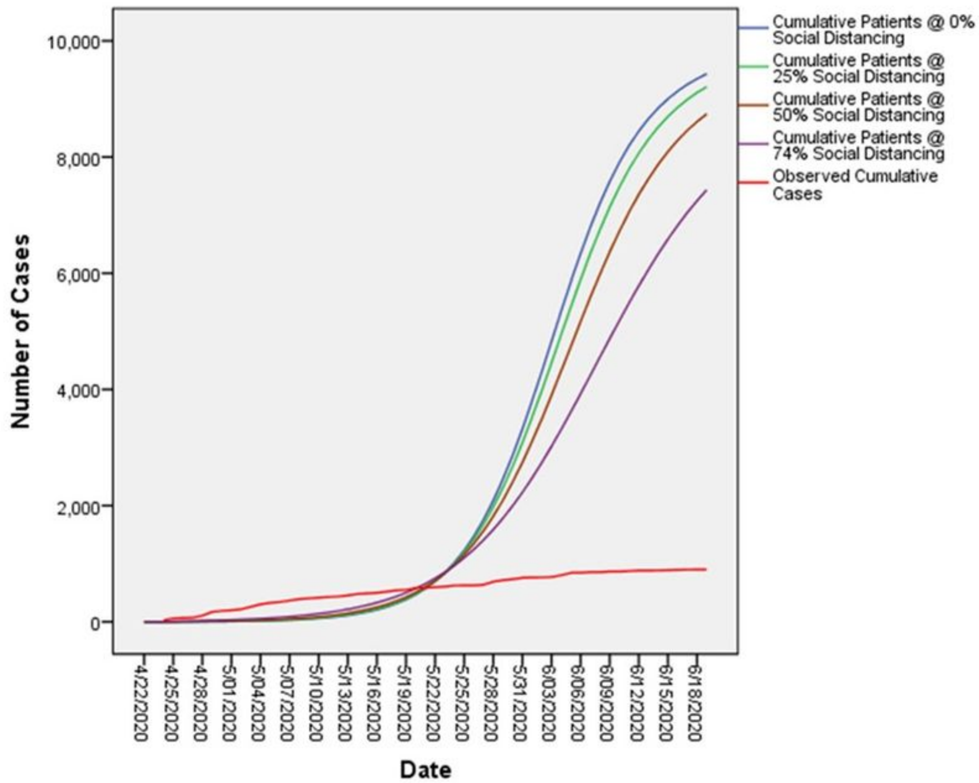

Figure 4

Projected and observed number of cumulative cases: The projected number of cumulative patients under 0%, 25%, 50% and 74% social distancing scenarios are shown in blue, green, brown and purple lines respectively. The red line shows the observed cumulative number of cases going above the lines showing cumulative number of cases under different social distancing scenarios until 20.05.2020. After that the red line showing the observed number of cases continue below the lines showing the cumulative number of projected cases. A steady decrease in the peak of projected curves is seen with rising social distancing levels.