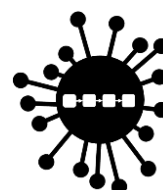

Modelling of COVID-19 Strategies in Nepal

Final Report

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Preface

Oxford Policy Management (OPM) and Oxford Policy and Analytics for Health of the Nuffield Department of Medicine, University of Oxford, have collaborated to respond to the pressing and urgent need to carry out modelling to predict the spread of COVID-19 in different countries. This report outlines the modelling of COVID-19 strategies in Nepal.

We are grateful to Mike Naylor, Mike Low, and Tanzia Ahmed from OPM for technical inputs and management support. This study has been funded by DFID's South Asia Research Hub (SARH). However, the views expressed herein do not necessarily reflect the official policies of the UK government.

Before delving into the details of the report, we briefly discuss the purpose of epidemiological models in the context of COVID-19. In detailing this, we draw on the World Health Organization's (WHO) note on what mathematical modelling is and how it can help control the COVID-19 epidemic (1). Mathematical models of infectious diseases provide an important tool for understanding the dynamics of infectious diseases, evaluating potential control strategies, and predicting future outbreaks. In the case of the ongoing COVID-19 outbreak, epidemiological models can be used to predict how the disease will spread in a population, and at the same time influence public health interventions to achieve the greatest impact (*Ibid.*). Such models may provide qualitative warnings regarding the potential dangers of lifting interventions prematurely, or for estimating the burden on the healthcare system.

It is also worth highlighting that epidemiological models incorporate a series of assumptions that may change as the outbreak continues and new data becomes available. With time, the models will mature and become more complex with the emergence of more data. However, COVID-19 is still very much a new disease and there are important aspects of the disease we do not yet know much about (*Ibid.*). This makes simulating the spread of the disease particularly challenging. For this reason, we emphasise that epidemiological models are simply one of many tools at the disposal of policymakers, all of which rely on the collection, dissemination, and analysis of high-quality epidemiological data. An appropriate analogy is to think of them as weather forecasts, which simulate a projection based on past experience and present determinants.

In summary, we emphasise the importance of policymakers relying on a series of high-quality epidemiological instruments that work collaboratively together to guide, but not dictate, policy decisions. Mathematical models are among these instruments (*Ibid.*).

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Executive summary

The COVID-19 pandemic is rapidly spreading across the globe with high mortality, severely straining health systems and causing significant social disruptions and economic damage. Like many other developing countries with suboptimal health systems and capacity, Nepal may also suffer significantly due to the impact of COVID-19. Mathematical modelling using epidemiological data can help policymakers to better understand the impact of the various mitigation strategies on transmission of the virus and mechanisms for ‘flattening of the curve’, as well as which intervention would be most effective. DFID has commissioned OPM and the University of Oxford to carry out a rapid modelling of the possible spread of COVID-19 in Nepal.

We developed a SEIR (Susceptible (S), Exposed (E), Infectious (I), Recovered (R)) compartmental model. The model uses a series of age-stratified deterministic ordinary differential equations, implemented in the statistical software R. The model does not take a system-wide perspective on modelling the overall impact of COVID-19, but instead estimates the direct burden of COVID-19 on the healthcare system in Nepal. As Nepal is continuing with a range of non-pharmaceutical interventions (NPIs) first implemented in March, we analysed the impact of three disruption strategies, labelled the ‘low disruption strategy’, ‘medium disruption strategy’, and ‘high disruption strategy’. Each strategy differs by the degree of social and economic disruption we anticipate they could cause to the general population. The low disruption strategy assumes the interventions first implemented by the Government of Nepal (GoN) will end abruptly after 8–10 weeks from the date they were introduced. The medium disruption strategy extends handwashing interventions, school closures, and the limitations on imported cases for an additional 26 weeks from when they are intended to be lifted. Lastly, the high disruption strategy extends the self-isolation, voluntary home quarantine, and handwashing interventions for an additional 16 weeks from when they were first intended to be lifted.

Under the low disruption strategy, the model estimates 81% of the population will be infected by the end of the year and the peak will occur between June and September. Additionally, the model estimates that COVID-19 could result in 49,200 deaths by the end of the year, which would be roughly 25% of all-cause mortality¹. The model estimates that the medium disruption strategy will reduce the burden of the disease by approximately 5,000 cumulative deaths compared to the low disruption strategy, accounting for 23% of all-cause mortality by the end of the year. Under this strategy, the model estimates that the peak of infection will occur between July and October. The high disruption strategy incurs the lowest number of deaths, reducing the cumulative mortality by approximately 15,800 deaths compared to the low disruption strategy, which would account for 19% of all-cause mortality by the end of the year. Under this scenario, the peak of infection is estimated to occur between June and September.

We emphasise the significant levels of uncertainty surrounding the results presented in this analysis. While every effort has been made to ensure the model is as accurate and as

¹ All-cause mortality refers to all the deaths that occur in a population regardless of the cause, including those that result from COVID-19.

reliable as possible, the model is based on a series of assumptions relating to the disease severity and mortality, the coverage and adherence of the various interventions among the population, and the underreporting of symptomatic and asymptomatic infections. Significant levels of uncertainty exist in each of these parameters, which, when compounded together, contribute to further uncertainty in the model results. For this reason, it is important to understand these results are only rough approximate estimates of potential future scenarios.

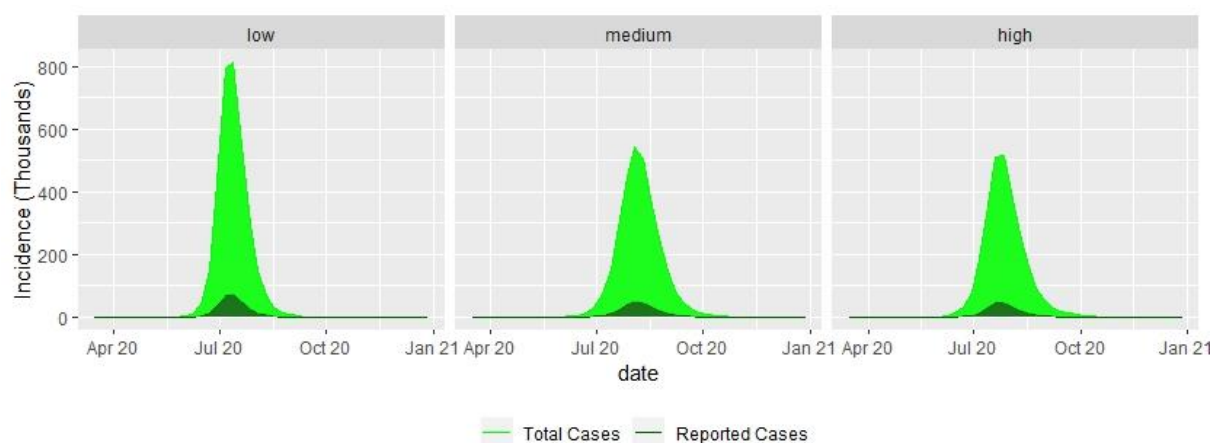
Despite the uncertainties and the caveats attached to the changing scenarios, the high disruption strategy seems to significantly reduce the burden of the disease. Thus, it might be worthwhile to implement that strategy for the next few months and review it on a regular basis. We recognise the level of social and economic disruption this may potentially cause to the majority of the population in Nepal, emphasising the importance of implementing these interventions in conjunction with social protection and food security measures. Further modelling could involve assessing the sensitivity of the results to the model parameters, conducting a sub-national analysis, or investigating the impact of other intervention strategies. We also recommend using additional evidence from other public health, social protection, and economic analyses to ensure that the policy decisions are made using evidence that is context specific and applicable.

Policymakers' summary

This report provides model-based estimates for various disruption strategies relating to the COVID-19 epidemic in Nepal. 'Disruption strategies' refers to the package of interventions the GoN may implement after the current interventions are eased. We take the total population of Nepal to be 29 million, with an average age of 22 years (2). The age structure, demographic characteristics, and social contact patterns of the Nepali population are taken into account using a transmission model to estimate the spread of the disease among the population. We estimate the magnitude and approximate timing of the burden of COVID-19 in terms of the daily incidence (i.e. number of new cases per day), deaths, and hospital demand (i.e. intensive care unit (ICU) bed occupancy and number of ventilators). It is important to note that the model does not take a system-wide perspective on modelling the overall impact of COVID-19, but instead estimates the direct burden of COVID-19 on the healthcare system in Nepal.

We analyse the impact of three strategies for the GoN to consider after the current interventions have ended. Each strategy is a combination of various NPIs. They have been ordered by the degree of disruption we consider they will have in the context of Nepal. The low disruption strategy estimates the burden of the disease if all the current interventions were lifted on 18 May 2020. The medium disruption strategy extends the duration of several interventions that we perceive to be less socially or economically disruptive in the context of Nepal. In contrast, the high disruption strategy includes interventions we have found to be the most impactful, due to the estimations involved in this model as well as experience of modelling the spread of COVID-19 in various other countries. However, these interventions also tend to be the most disruptive and difficult to implement.

Figure 1: Disease incidence under the low, medium, and high disruption strategies



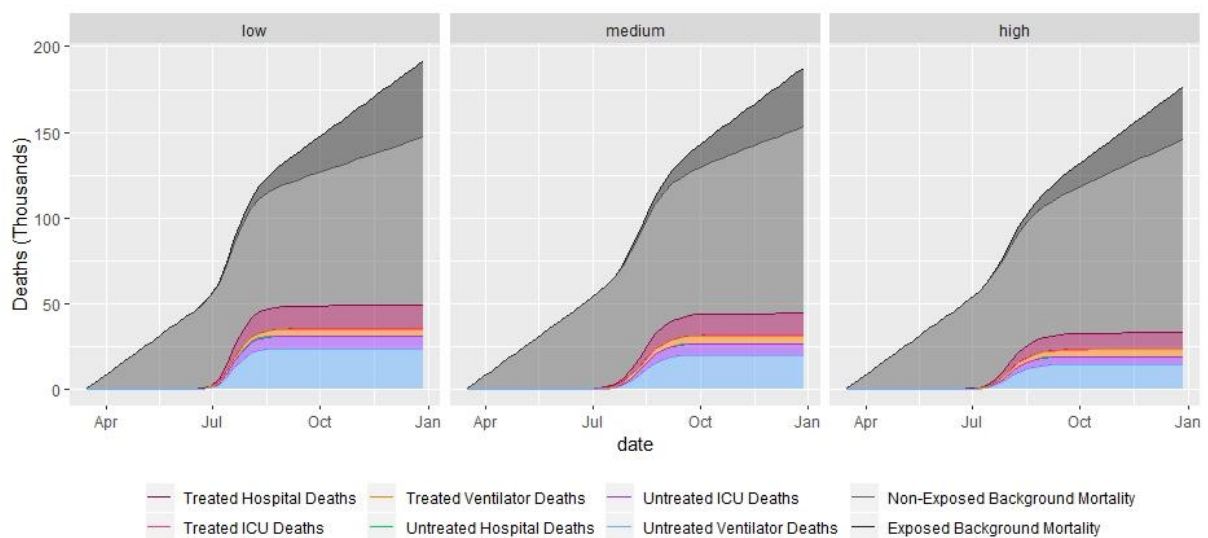
The results of the modelling exercise for each strategy are presented in Figure 1, which shows the daily disease incidence, and Figure 2, which shows the cumulative disease mortality (i.e. the total number of deaths). Under the low disruption strategy, we estimate the peak of the disease incidence will reach 75,000 new cases per day and will occur between June and September. Under the medium disruption strategy, we predict the peak disease incidence will decrease significantly to 50,000 new cases per day and will occur between July and October. The high disruption strategy, which is the most extreme of the three

strategies considered, estimates the peak in the disease incidence will only marginally reduce to 46,800 new reported cases per day and will likely occur between the period of mid-June and October. We have assumed that only a small proportion of cases are reported to the healthcare system, increasing the total number of cases significantly. We estimate that, by the end of the year, under the low disruption strategy 81% of the population will have become infected with the disease. This estimate decreases to 71.3% under the medium disruption strategy, and to 64.8% under the high disruption strategy.

Under the low disruption strategy, we estimate that the number of deaths from COVID-19 will reach 49,000 deaths by the end of the year, equating to 25% of all-cause mortality by the end of the year. The number of deaths under the medium disruption strategy decreases only slightly to 44,000 deaths, representing 23% of all-cause mortality by the end of the year. The high disruption strategy shows a greater impact in terms of the reduction in disease mortality, limiting the disease to 32,900 deaths. This equates to only 19% of all-cause mortality by the end of the year.

We also estimate the ICU bed occupancy and the utilisation of ventilators for each strategy. Under the low disruption strategy, the number of ICU beds occupied may reach 12,400, but reduces to 8,000 under the medium disruption strategy, and further to 6,000 under the high disruption strategy. In contrast, the estimated occupancy for ventilators does not appear to change significantly, remaining roughly the same across all disruption strategies at approximately 1,000 ventilators at the peak of the epidemic. However, it is worth emphasising that the health system – in terms of both of these measures – will very quickly be over-utilised under any strategy the government chooses to enact.

Figure 2: Disease mortality under the low, medium, and high disruption strategies



We emphasise caution when interpreting these results, as the model they are based on is the product of a series of assumptions, including ones relating to disease severity and mortality, the coverage and adherence of various interventions among the population, underreporting of deaths, and symptomatic and asymptomatic cases. While every effort has been made to ensure the model is as accurate and reliable as possible, a significant degree of uncertainty still remains. For this reason, it is important to understand these results are only rough approximate estimates of potential future scenarios.

Table of contents

Executive summary	i
Policymakers' summary	iii
List of abbreviations	vi
1 Introduction	1
1.1 Background.....	1
1.2 Current interventions in Nepal.....	1
1.3 Objectives.....	2
2 Methods	3
2.1 Model description.....	3
2.2 Limitations of the model.....	4
2.3 Interventions and disruption strategies.....	5
3 Results	10
3.1 Low disruption strategy results.....	10
3.2 Medium disruption strategy results.....	12
3.3 High disruption strategy results.....	14
3.4 Occupancy of ICU beds and ventilators	16
4 Discussion.....	18
5 Conclusion	21
5.1 Summary of key findings.....	21
5.2 Significance of these findings.....	22
5.3 Further analysis of the modelling	22
References	24
Annex A Terms of Reference	26
Annex B Model description.....	30
Annex C Model calibration.....	34
Annex D Description of disruption strategies	35
Annex E Description of interventions.....	38

List of abbreviations

DFID	Department for International Development
GoN	Government of Nepal
ICU	Intensive Care Unit
NPI	Non-Pharmaceutical Intervention
OPM	Oxford Policy Management
SARH	South Asia Research Hub
SEIR	Susceptible–Exposed–Infectious–Recovered infectious disease model
WHO	World Health Organization

1 Introduction

1.1 Background

The COVID-19 pandemic is rapidly spreading across the globe with high mortality, severely straining health systems and causing significant social disruptions and economic damage. As at 6 May 2020, there were nearly 3.8 million confirmed cases and nearly 265,000 deaths in 213 countries and territories (3).

Like many other developing countries with suboptimal health systems and capacity, Nepal, a South Asian country with a population of more than 28 million (2), could suffer significantly due to the impact of COVID-19. As at 6 May 2020, Nepal had reported 99 confirmed cases of COVID-19 with no deaths (4). So far, more than half of the cases reported in Nepal are imported cases and the vast majority of all reported cases are asymptomatic (5).

At this early stage of the pandemic in country, an evidence-based approach to predicting the temporal-spatial spread of the disease can be extremely useful for policymakers, helping them to better understand the likely severity of the disease, plan for surge capacity, and ascertain how to respond to save lives.

At present, there are no pharmaceutical interventions available and countries are relying on NPIs, which fall into various categories of behaviour change. These include: self-isolation for symptomatic individuals; increased hand hygiene; social distancing; working from home where possible; and school closure (6). In order to facilitate the appropriate selection of NPIs, it is important to estimate the impact of the various mitigation strategies on the progression of transmission of the disease (7).

Mathematical modelling using epidemiological data can provide this information, helping policymakers to better understand:

- The impact of the various mitigation strategies on transmission of the virus and mechanisms for 'flattening of the curve', as well as which NPIs will be more effective in their specific contexts;
- The anticipated demand for hospital and ICU beds at various levels of the health system; and
- The quantity of tests, personal protective equipment, ventilators, and other supportive tools needed in the diagnosis and treatment of patients.

This report outlines the results of the mathematical modelling of COVID-19 scenarios using different strategies that can be considered in Nepal.

1.2 Current interventions in Nepal

Here, we list the initial interventions Nepal has implemented in order to prevent the spread of COVID-19 throughout the country. The initial intervention mainly focused on communication, raising awareness, and self-isolation for those people with symptoms and started from 12 March. At that stage, information regarding the importance of handwashing and sanitation, use of masks, and self-isolation for those with flu-like symptoms were actively disseminated.

The GoN also asked people who live in the same household with people who show COVID-19 symptoms to voluntarily quarantine themselves in their houses. School closures were enacted on 19 March, and were quickly followed by a ban on all international travel in and out of the country. Even though the number of positive cases in Nepal was very low, these measures, although extreme for the stage of infection the country was in, were taken to curtail the spread of infection, which otherwise could have overwhelmed the country's weak health system.

1.3 Objectives

The objectives of this assignment are to:

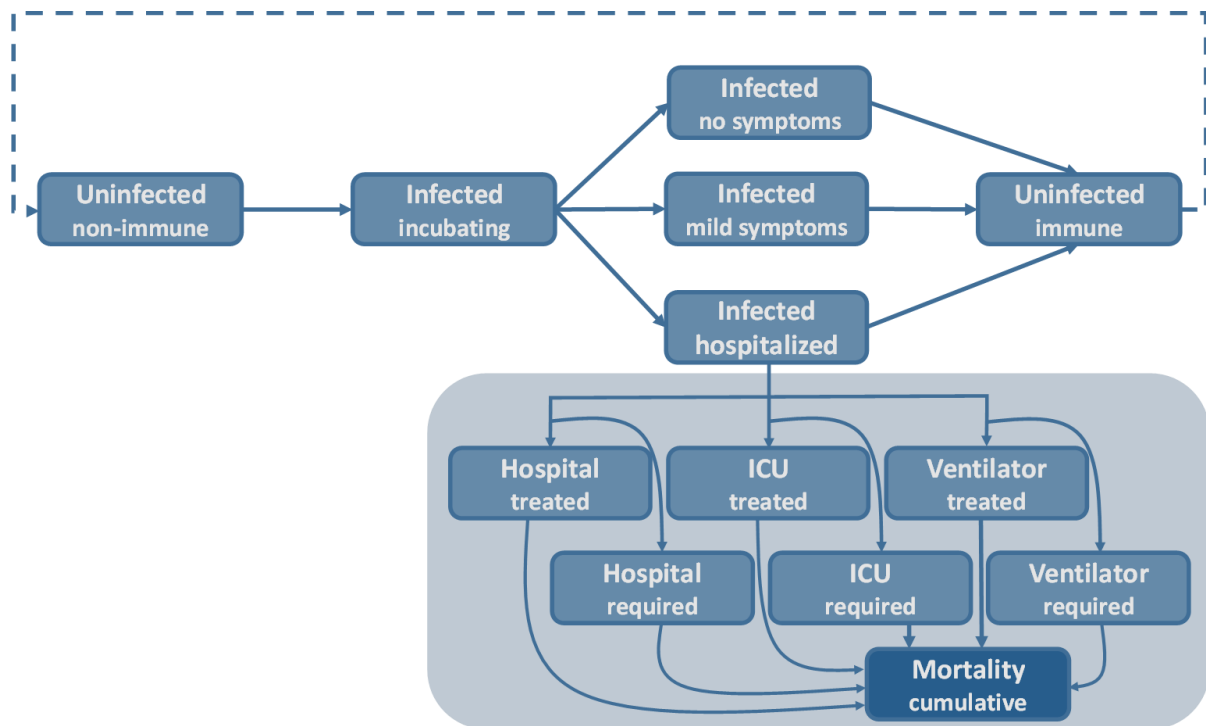
- Explore the potential effects of various future strategies on the time of the peak of the disease burden in Nepal;
- Predict the potential impact of limitations in health system capacity, including hospital beds and critical care units, during the epidemic;
- Identify the impact of potential strategies for release from the current interventions in place; and
- Identify priorities for further research.

2 Methods

2.1 Model description

We used an age-structured, compartmental SEIR model to estimate the burden of COVID-19 and the impact of various behavioural change strategies. The infected compartments were stratified by symptoms, severity, and those who have access to treatment and those who have been denied. A diagram of the model is shown in Figure 3. Further details of the model are provided in Annex B.

The model was populated with 2020 demographic data for Nepal, stratified by age (8). As COVID-19 is transmitted through social contacts between infected and susceptible individuals, it is imperative to incorporate this mechanism into the model structure. This was achieved using data from (9), which provides the social contact patterns of 152 countries, Nepal being among them, at a national level in four different settings: home, work, school, and other locations. As COVID-19 severity and mortality are both highly dependent on an individual's age, the model uses disease severity and mortality rates stratified by age (10,11). The data we used to estimate the health system capacity in Nepal was provided by the national Ministry of Health and Population (12). To ensure the model accurately represents the situation in Nepal as best it can, the model is fitted to the number of confirmed cases that have been reported in the country to date (13). We were limited by the availability of data relating to the coverage and adherence of the interventions, both those that have been implemented to date and potential future interventions the GoN may be willing to consider. To circumvent the lack of data in this regard, we made various assumptions based on our experience of the context of Nepal in order to estimate the coverage and adherence of the various interventions. The interventions are described in more detail in Section 2.3.

Figure 3: Diagram of the model and the relation between variables

2.2 Limitations of the model

The model has several limitations, which are presented below:

1. Although the model takes into account the age structure of the population, due to the structure of the model we are unable to account for household- and individual-level heterogeneity in the population.
 - a. Individual heterogeneity among the population could be important in super-spreading events, particularly early in an epidemic.
 - b. Combined with nosocomial infections, the risk of COVID-19 infection is potentially amplified with close contact between confirmed cases and healthcare workers. However, the current model is not equipped to explicitly consider transmission within healthcare institutions.
2. The model currently does not consider spatially correlated data and assumes that the burden of disease is uniformly distributed across a given region.
 - a. Due to the major health facilities being located in the capital and other big cities, it is expected that a large percentage of the population will migrate to such places to seek healthcare, potentially leading to future transmission of the disease.

3. This model does not take into account the economic impact of implementing the interventions outlined.
 - a. Given the vulnerable conditions that many people in Nepal are living under, it may be that the economic cost of a specific intervention may cause greater repercussions than the disease itself.
4. Given the early status of the epidemic and the lack of adequate reporting in Nepal, as well as uncertainties around host immunity factors, environmental factors, and reporting rates for asymptomatic and symptomatic COVID-19 infections, the model makes assumptions based on experiences in other settings, which might have systematically affected the findings.
 - a. We assumed that the current reporting rate of symptomatic cases is 10% and that of asymptomatic cases is 5% while calibrating the model (see Annex C).
 - b. As community testing is not currently being carried out in Nepal at the time of writing, there is huge uncertainty around the unreported reservoir of infections in the community and the output of the results will change with change in these parameter values when more reliable data is available.
5. Uncertainties in the model estimates arise from uncertainties in disease parameters and assumptions regarding the coverage and effectiveness of the interventions.
 - a. It is important to note that the intervention's coverage and effectiveness are affected by a variety of social, cultural, and economic factors.
 - b. It should be expected that the model outputs will change as more is learnt about the disease.
6. The model has not accounted for various co-morbidities prevalent in the Nepali population.
 - a. Understanding the effect co-morbidities will have on the population may be of particular interest to policymakers as many co-morbidities are prevalent across Nepal (14).
 - b. It is possible the effect of co-morbidities could be implemented in future versions of the model.
7. We have not included seasonality due to a lack of evidence on whether this epidemic will have a seasonal pattern and, if so, whether it will have the same pattern as flu.

2.3 Interventions and disruption strategies

Interventions aimed at containing the spread of infection will inevitably cause disruptions in the lives of people and the country overall. Below we present a range of potential disruption strategies, specific to the context of Nepal, which vary in terms of the degree of disruption we consider them to have on the daily lives of people living in Nepal and on the local economy.

The three disruption strategies are proposed to study the impact that various sets of interventions can have on the case load in the country, when in place for a particular time-period. The various disruption strategies are also listed in Table 1 and described in more detail in Annex D. A timeline of the interventions considered in each strategy is provided in Figure 4. Due to the lack of available data, we used our collective experience of working in Nepal to estimate the effectiveness, coverage, and level of adherence to the various interventions the GoN has implemented in the past, as well as the interventions in each of the disruption strategies described below.

1. Low disruption strategy

The low disruption strategy assumes the initial set of interventions the country is under (see Section 1.2) will be lifted after eight to 10 weeks from when they were implemented. After the various interventions are lifted, all restrictions relating to the strategy – including self-isolation of suspected cases and voluntary quarantining of those who live in the same household, social distancing, handwashing, school closures, and limitation of imported cases – will be removed.

This strategy estimates the impact of removing all the interventions in place on their respective date. This strategy enables us to evaluate the impact these interventions will have by averting the incidence and number of deaths over the weeks. It is also important to mention that the duration of the interventions was to last for eight to ten weeks as set by the GoN, which was what was then used in the model. At the time of writing, however, these have been further extended by an additional two weeks.

2. Medium disruption strategy

We consider that it is not feasible for the initial interventions to be extended indefinitely in the context of Nepal. Therefore, interventions we consider to be helpful in maintaining a low case load, while allowing near normal life to resume, have been grouped together to evaluate the incidence of infection along with mortality. The medium disruption strategy continues the less disruptive components of the initial set of interventions for an extended period of time. These are:

- School closures (extended for an additional 26 weeks from when they first were intended to be lifted on 18 May); and
- Handwashing and the limitation of imported cases (both extended for an additional 26 weeks from when they first were intended to be lifted on 18 May).

Children are relatively less prone to getting infected with COVID-19 but they can pose a risk to elderly family members due to family structures in Nepal, whereby extended family members often live in the same household. Additionally, sensitivities regarding children's health have also been kept in mind when selecting school closure as a viable intervention in the context of Nepal. This will cause some degree of disruption to daily life as parents will have additional responsibilities in terms of helping children with their studies as well as day-care. Similarly, travel restrictions are essential to prevent the importing of cases, as well as to prevent unnecessary strain on the health system. Handwashing should ideally be incorporated as a way of life, but for the requirement of this modelling it has been assigned to the designated time-period of the intervention.

The more disruptive components of the initial set of interventions were assumed to be discontinued when they were initially set to end. Included in this list are:

- Self-isolation of symptomatic people and home quarantine of those people who live in the same household; and
- Social distancing interventions (i.e. restrictions on people attending social gatherings).

3. High disruption strategy

The high disruption strategy involves continuing what we consider to be the most effective measures for containing the disease. Nonetheless, it should be noted that we recognise the magnitude of disruption these interventions may have on the daily lives of people living in Nepal and also on the local economy. Under this strategy, we have assumed the following interventions will continue:

- Handwashing (extended for an additional 26 weeks from when the interventions were first intended to be lifted on 18 May); and
- Self-isolation of symptomatic people and voluntary quarantine of those people who live in the same household (both extended for an additional 12 weeks from when they first were intended to be lifted on 18 May).

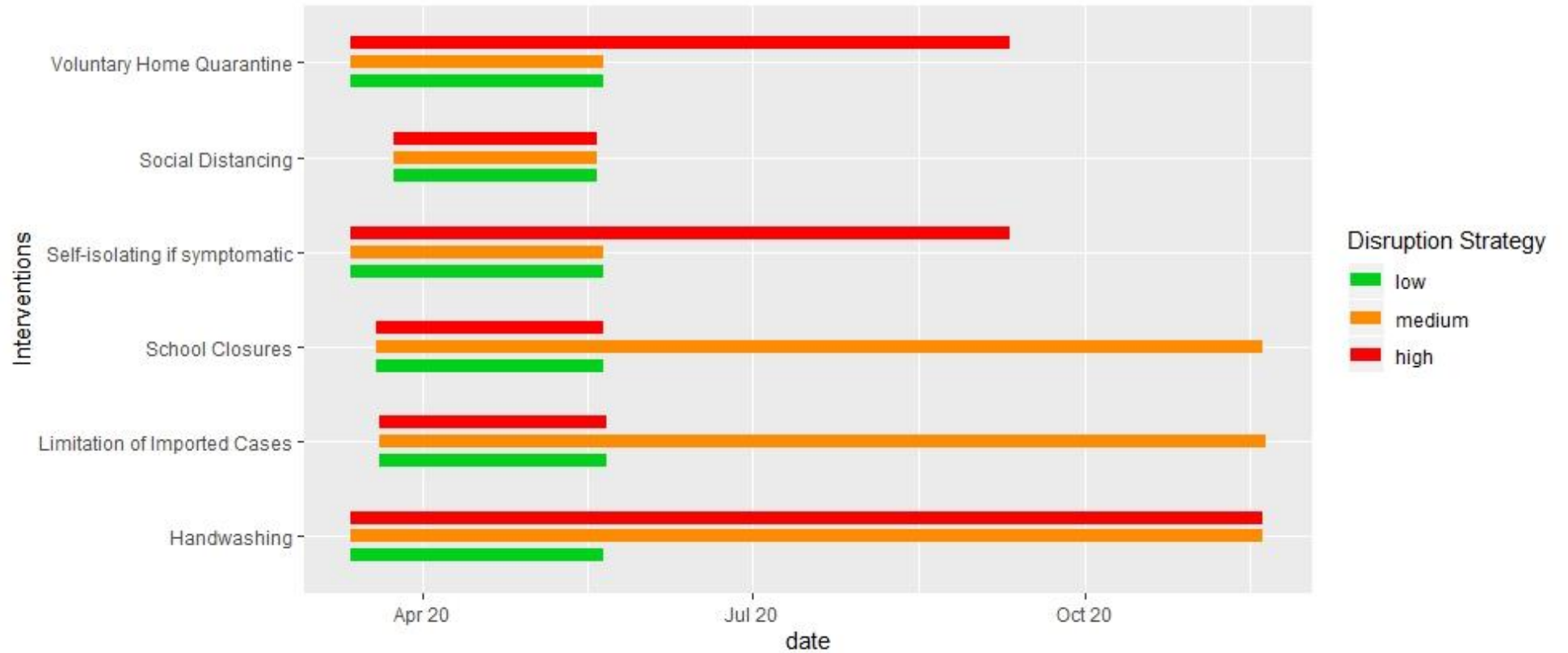
Other components of the initial set of interventions that were deemed less disruptive were assumed to be discontinued when they were initially set to end. Included in this list are:

- Social distancing (i.e. restrictions on people attending social gatherings);
- Limitation of imported cases; and
- School closures.

Self-isolating if symptomatic and voluntary quarantine will require entire households that have at least one member who is suspected of having COVID-19 to be confined to their house for a period of 14 days. We consider this to be an extremely disruptive measure in the context of Nepal and therefore suitable for this strategy. The three interventions retained under the high disruption strategy – i.e. handwashing, self-isolation if symptomatic, and voluntary quarantine, with high compliance – have a better chance of curtailing the spread of the disease. While social distancing is the most effective intervention in terms of curtailing the spread of infection, we consider this option to not be economically or socially viable in Nepal, partly due to the risk of non-effective compliance. As the world is attempting to go back to normalcy as much as is possible to maintain a sustainable economy, it will be important to explore interventions that are practical and feasible as well as viable.

Table 1: Parameters, start date, duration, and levels of the intervention strategies considered in the modelling

Intervention strategy	Parameters	Start date	Duration	Levels used in the parameters
Low disruption	Self-isolating if symptomatic	12/03/2020	10 weeks	Coverage= 50%, Adherence = 50%
	Social distancing	24/03/2020	8 weeks	Coverage= 70%, Adherence= 70%
	Handwashing	12/03/2020	10 weeks	Efficacy = 10%
	School closure	19/03/2020	9 weeks	Efficacy = 85%
	Limitation of imported cases	20/03/2020	9 weeks	Efficacy = 90%
	Voluntary quarantine	12/03/2020	10 weeks	Coverage = 20%
Medium disruption	Handwashing	12/03/2020	10 weeks + additional 26 weeks = 36 weeks	Efficacy = 10%
	School closure	19/03/2020	9 weeks + additional 26 weeks = 35 weeks	Efficacy = 85%
	Limitation of imported cases	20/03/2020	9 weeks + additional 26 weeks = 35 weeks	Efficacy = 90%
High disruption	Self-isolating if symptomatic	12/03/2020	10 weeks + additional 16 weeks = 26 weeks	Coverage= 50% Adherence= 50%
	Handwashing	12/03/2020	10 weeks + additional 26 weeks = 36 weeks	Efficacy = 10%
	Voluntary quarantine	12/03/2020	10 weeks + additional 16 weeks = 26 weeks	Coverage = 20%

Figure 4: Timeline of the interventions included in the three disruption strategies considered in the modelling

3 Results

In this section we present the results from the modelling exercise, estimating the potential impact of the three disruption strategies. The three disruption strategies represent the range of interventions the GoN can implement to reduce the burden of the disease. We anticipate the disruption the interventions will have on the lives of people living in Nepal will increase in scale from low to high.

While every effort has been taken to ensure the model is as accurate and reliable as possible, it is important that the relevant policymakers fully understand the limitations of the model, as highlighted in Section 2.2. Several parameters used in the model contain high levels of uncertainty, including the underreporting rates of symptomatic and asymptomatic infections, the probability of infection given a contact, disease severity and fatality rates, and assumptions regarding the effectiveness and coverage of various interventions (both those that have been implemented to date and potential interventions to be implemented in the future). Uncertainty in parameter estimates should be expected to contribute significantly to the variation in the model outputs. We therefore emphasise that the results from this analysis should be used with caution and in combination with a larger evidence base during decision-making processes. Additionally, the model results could change as we learn more about the disease itself and environmental factors and host immunity factors affecting transmission dynamics and outcomes in the context of Nepal and the impact of various interventions on the disease's nature.

3.1 Low disruption strategy results

Figure 5 shows the estimated number of new cases per day under the low disruption strategy (i.e. the current strategy) where all the interventions are expected to end around 20 May 2020 (reflecting to the government's strategy to continue the current interventions till 18 May 2020). The model estimates that, if the current interventions are lifted soon, 81.1% of the population will be infected by the end of the year with the peak of the epidemic extending from early June to early September, reaching a maximum of nearly 846,000 new cases per day with less than 10% of cases (75,000) reported to the health system. These model estimates are sensitive to the assumption of low reporting rates (i.e. 5% for asymptomatic cases and 10% for symptomatic cases) and should be interpreted cautiously.

Figure 5: Predicted incidence of new cases per day under the low disruption strategy

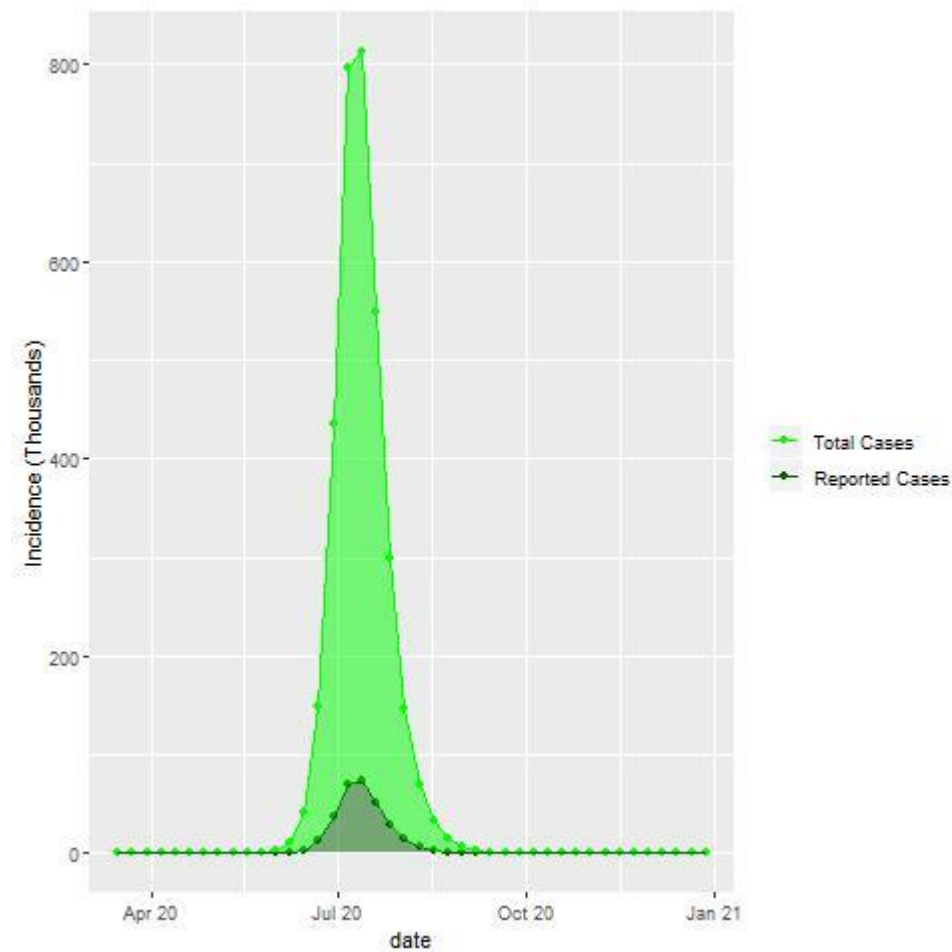
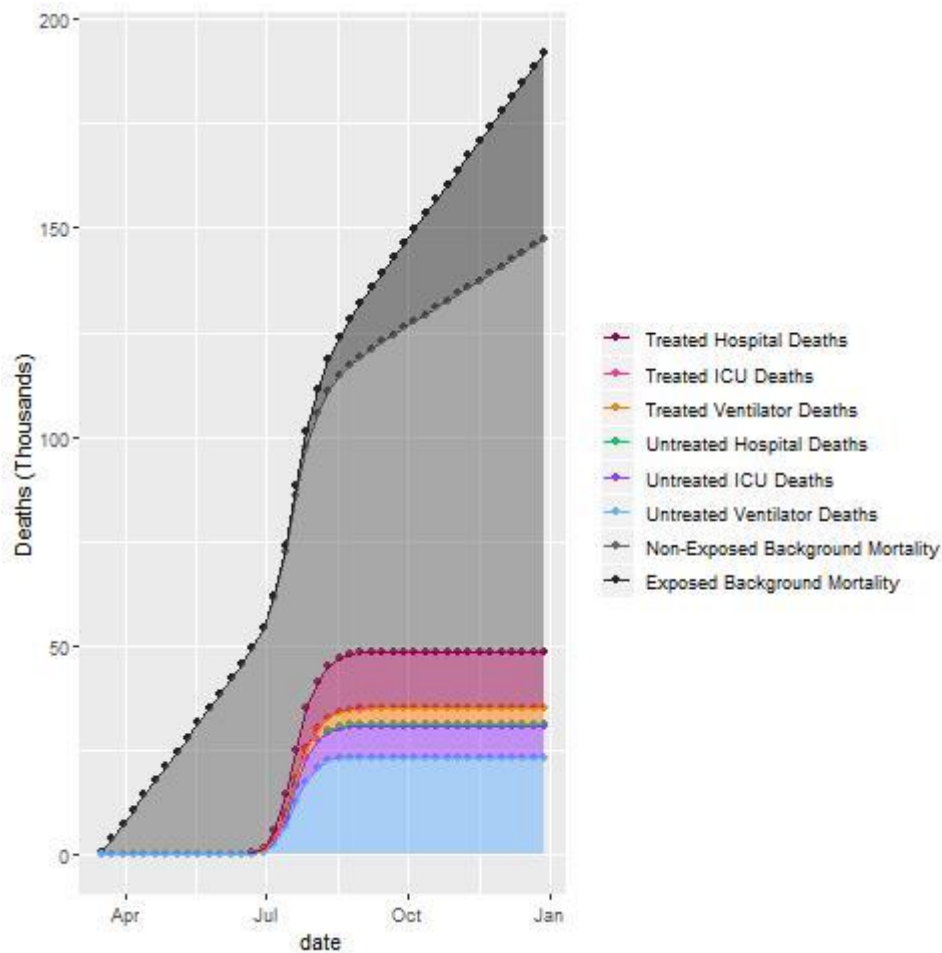


Figure 6 shows the projected number of cumulative deaths under the low disruption strategy. The model estimates 49,200 cumulative deaths due to COVID-19 by the end of the year. A large proportion of these deaths are expected to be from untreated cases. ICU cases without ventilator treatment alone are predicted to account for a total of 23,200 deaths.

Among the projected all-cause cumulative deaths of 193,000 by the end of the year, cumulative natural deaths account for 144,000 (99,000 natural deaths in the non-exposed group and 45,000 in the COVID-19 exposed group). Under the low disruption strategy, COVID-19 is expected to account for 25% of all-cause mortality by the end of the year. That said, we emphasise again the significant uncertainty in these model estimates given the uncertainty in the assumptions relating to the coverage and effectiveness of the interventions. For instance, the coverage and efficacy of self-isolation measures were assumed to be 50% each, and those of social distancing to be 70% each. In the absence of direct data, these assumptions have been based on proxy estimates from our experience and the results will change with these assumptions.

Figure 6: Predicted mortality under the low disruption strategy

Under the low disruption strategy, we anticipate that the current measures will continue for some time and then will be abruptly lifted without further measures being put in place. The modelling results indicate that this will likely lead to a full-scale epidemic at a later date. This is due to the fact that, after the interventions are lifted, the disease will likely remain prevalent while a large proportion of people are still susceptible to being infected. Hence, we predict that lifting the interventions and immediately returning to a pre-intervention state will likely only delay the epidemic and will ultimately have very little impact.

3.2 Medium disruption strategy results

Figure 7 presents the incidence of new cases per day under the medium disruption strategy. Under this disruption strategy, the model predicts that 73.1% of the population will be infected by the end of the year with the peak of the epidemic extending from mid-July to early October, reaching a maximum of nearly 548,000 new cases per day with less than 10% (50,000) of cases being reported to the health system. These model estimates are sensitive to the assumption of low reporting rates (5% for asymptomatic cases and 10% for symptomatic cases) and should be interpreted cautiously.

Compared to the low disruption strategy, the medium disruption strategy is expected to decrease new infections by 18%, and the maximum cases reported to the health system per day by 25,000. We assume that the efficacy of hand hygiene, school closures, and travel

bans to be 20%, 85%, and 90%, respectively, in preventing transmission. It should be noted that these results are highly sensitive to even small variations in both the disease-specific parameters and the intervention parameters. Due to a lack of available data, we used our experience and understanding of the context of Nepal to roughly estimate the parameters relevant to each intervention, including their coverage, adherence, and effectiveness.

Figure 7: Predicted incidence under the medium disruption strategy

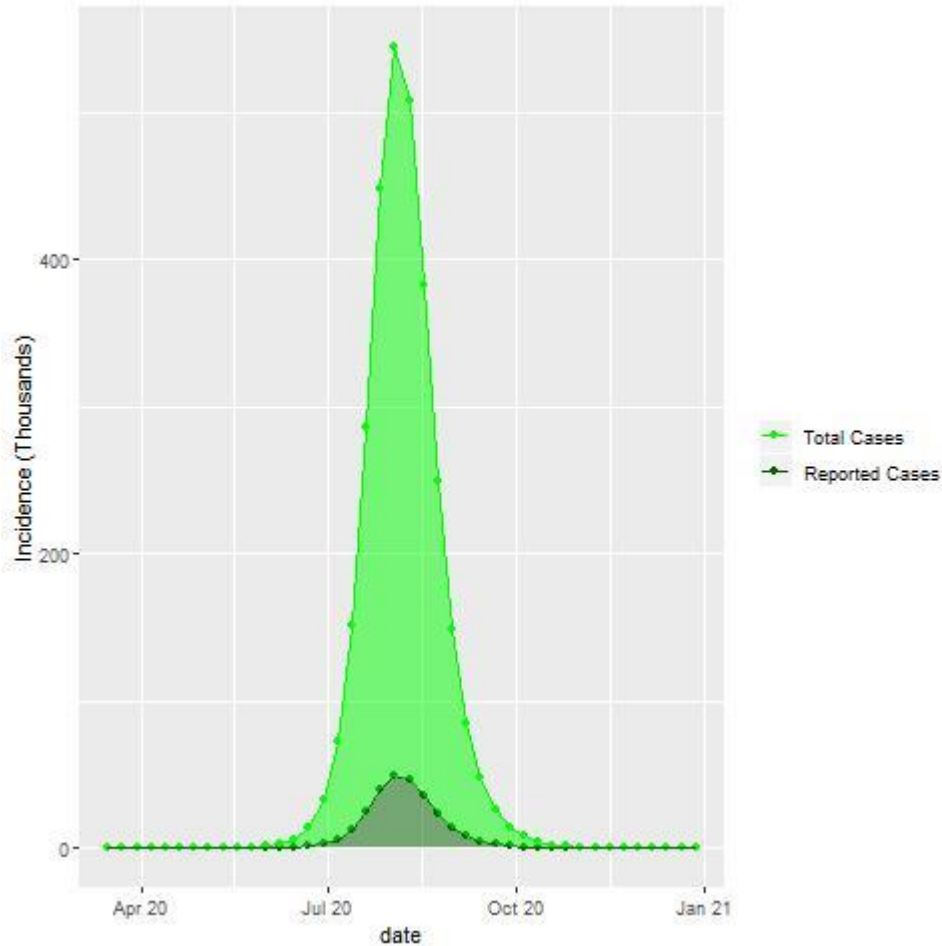
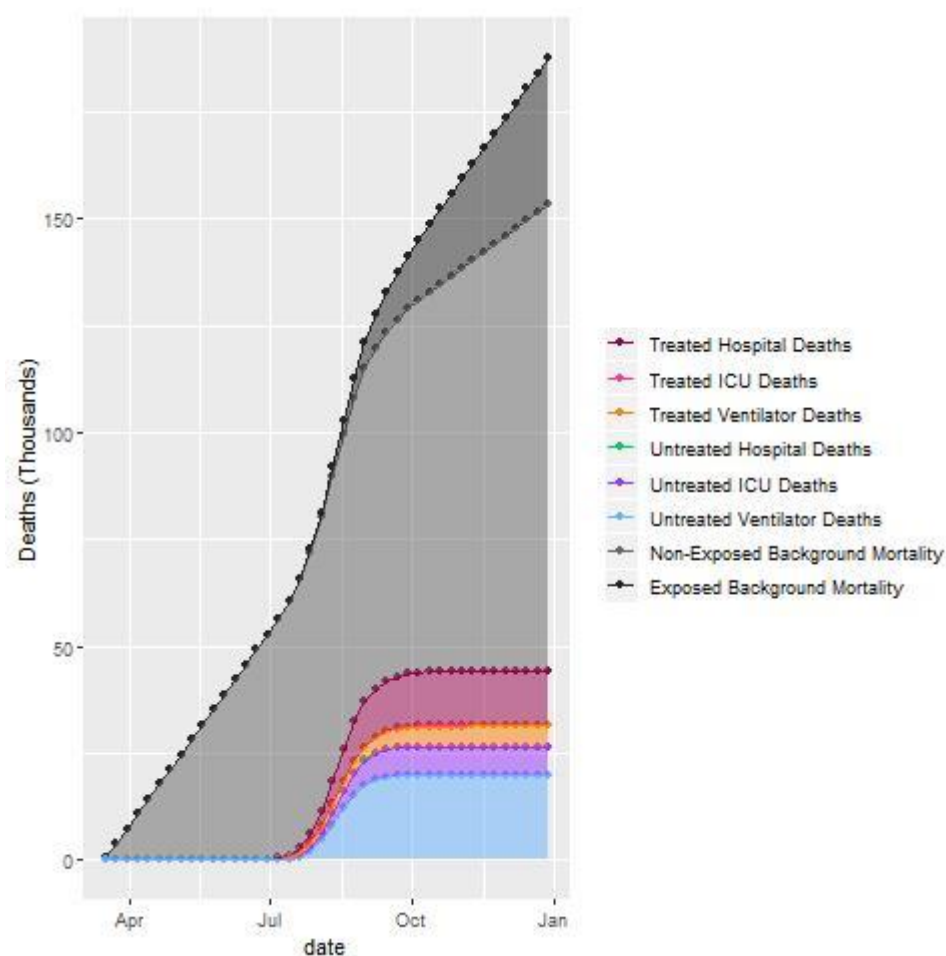


Figure 8 shows the projected number of cumulative deaths under the medium disruption strategy. The model estimates 44,200 cumulative deaths by the end of the year and a large proportion of these deaths are predicted to be from untreated cases. Compared to the low disruption strategy, the medium disruption strategy is expected to lower the cumulative deaths by around 5,000 by the end of the year. As with the low disruption strategy, ICU cases without ventilator treatment alone are predicted to account for the largest contribution (19,700).

Among the projected all-cause cumulative deaths of 188,000 by the end of the year, cumulative natural deaths account for 144,000 (109,000 natural deaths in the non-exposed group and 35,000 in the COVID-19 exposed group). Under the medium disruption strategy, COVID-19 is expected to account for 23% of all-cause mortality by the end of the year.

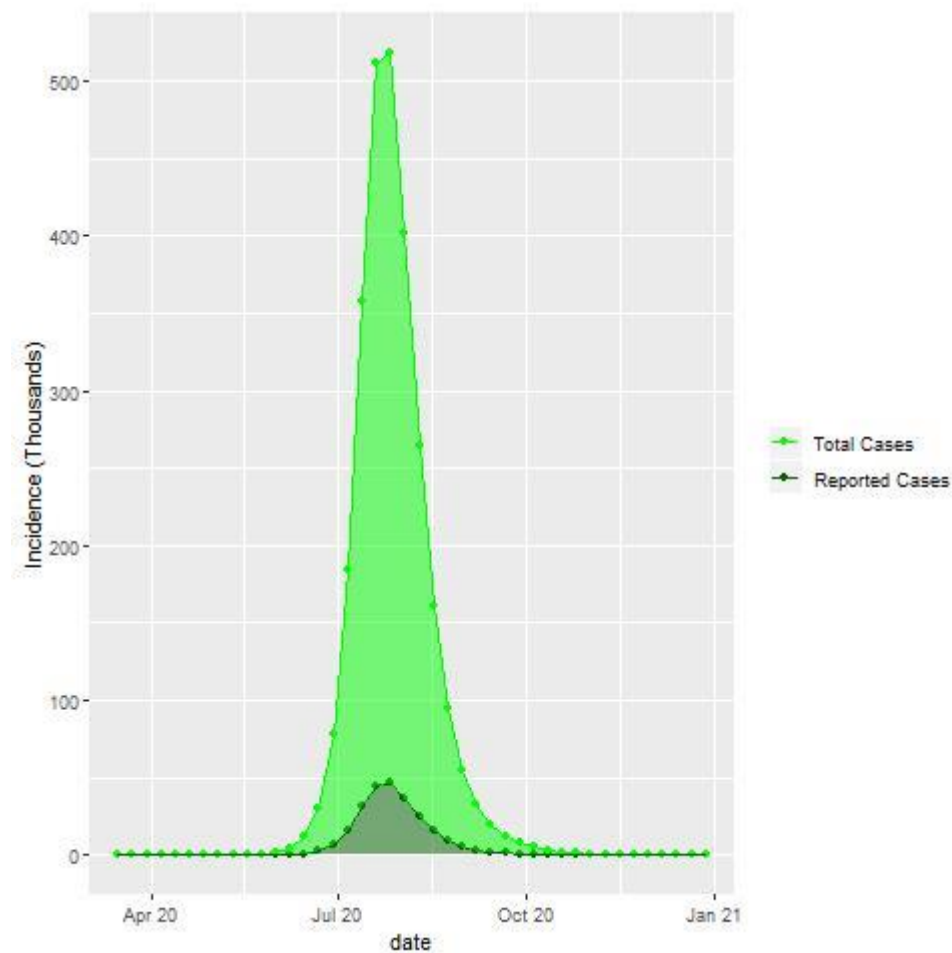
Figure 8: Predicted mortality under the medium disruption strategy

3.3 High disruption strategy results

Figure 9 shows the incidence of new cases per day under the high disruption strategy. Under this disruption strategy, the model predicts that 64.8% of the population will be infected by the end of the year with the peak of the epidemic extending from mid-June to late October, reaching a maximum of nearly 531,000 new cases per day with less than 10% of cases (46,800) reported to the health system. Again, these model estimates are sensitive to the assumption of low reporting rates (5% for asymptomatic cases and 10% for symptomatic cases).

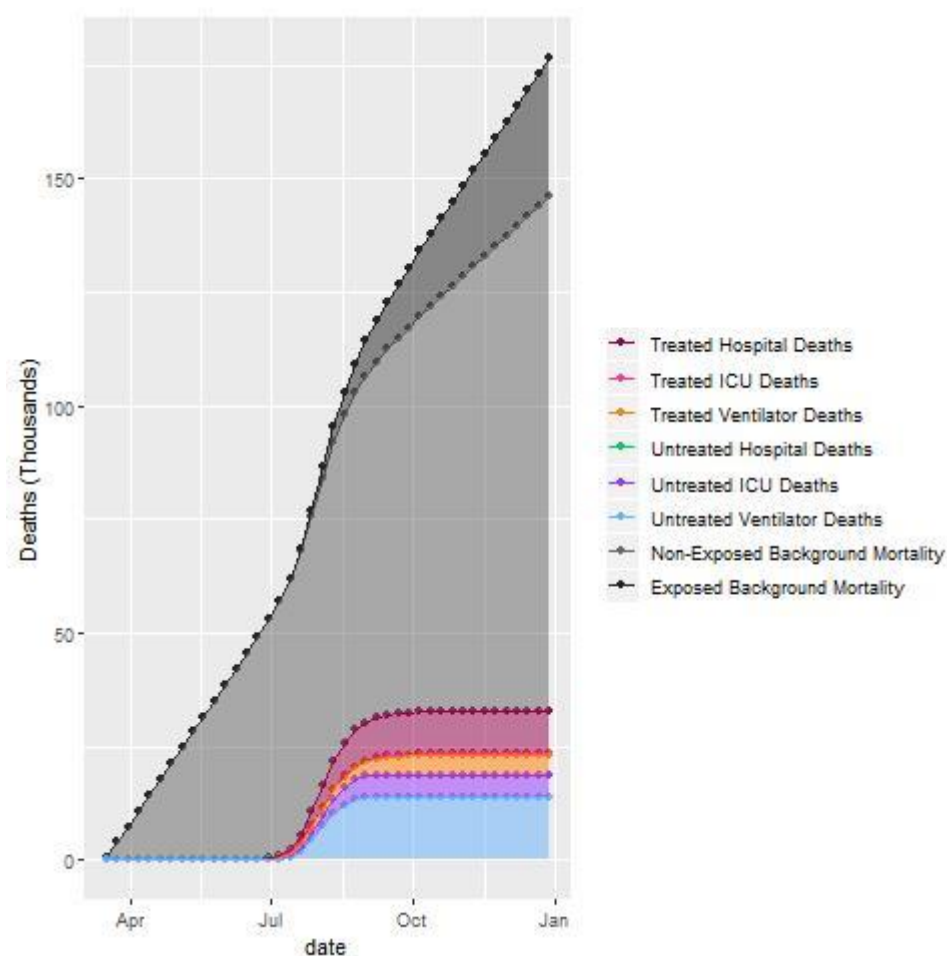
We assume the coverage and efficacy of self-isolation measures to be 50% each, the coverage of home quarantine to be 20%, and the efficacy of hand hygiene practices in preventing transmission to be 10%. These results are highly sensitive to even small variations in the parameters included in the model, many of which vary over a wide interval. Due to the uncertainty in the model estimates, we emphasise caution when interpreting these results. The figures reported here are only approximate estimates and should be expected to vary significantly in practice.

Compared to the low disruption strategy, the high disruption strategy is expected to decrease new infections by 16%, decreasing the maximum cases reported to the health system per day by 26,000.

Figure 9: Predicted incidence under the high disruption strategy

In this strategy, the model estimates 32,900 cumulative deaths by the end of the year and a large proportion of deaths are predicted to be from untreated cases (see Figure 10). The high disruption strategy is predicted to lower the cumulative deaths by around 16,300 compared to the low disruption strategy and by 11,300 compared to the medium disruption strategy by the end of the year. Again, ICU cases without ventilator treatment alone are predicted to account for the largest contribution to total deaths (14,000).

Among the projected all-cause cumulative deaths of 176,000 by the end of the year, cumulative natural deaths account for 144,000 (114,000 natural deaths in the non-exposed group and 31,000 in the COVID-19 exposed group). Under the high disruption strategy, COVID-19 is expected to account for 19% of all-cause mortality by the end of the year.

Figure 10: Predicted mortality under the high disruption strategy

3.4 Occupancy of ICU beds and ventilators

Figure 11 and Figure 12 illustrate the burden on the healthcare system in terms of ICU beds and ventilators. The horizontal black line in each figure indicates the current capacity of ICU beds and ventilators in Nepal, respectively. The model predicts that 12,400 ICU beds will be occupied under the low disruption strategy. Under the medium and high disruption strategies, the model estimates the required number of ICU beds will decrease to 8,000 and 6,600, respectively. Conversely, the model estimates the utilisation of ventilators will remain largely the same across each of the interventions, and is expected to be of the order of 1,000 ventilators. The current health system capacity in Nepal is composed of approximately 1,600 ICU beds and 600 ventilators. The model predicts that large increases in the number of ICU beds (an increase of 5,000–11,000) and ventilators (an increase in number of approximately 400) are required to accommodate the treatment of cases.

We emphasise that the ICU bed occupancy and ventilator utilisation estimates need to be interpreted with caution, as they are highly sensitive to both the disease and intervention parameters. The parameters used to inform the model exhibit significant degrees of uncertainty that, ultimately, propagate through to the model outputs.

Figure 11: Predicted ICU occupancy under different scenarios

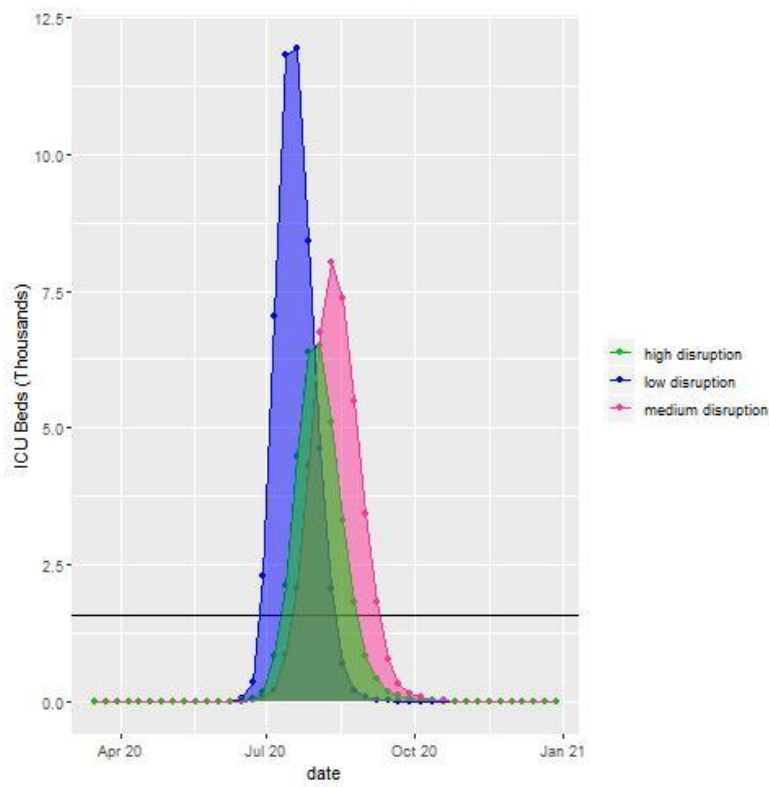
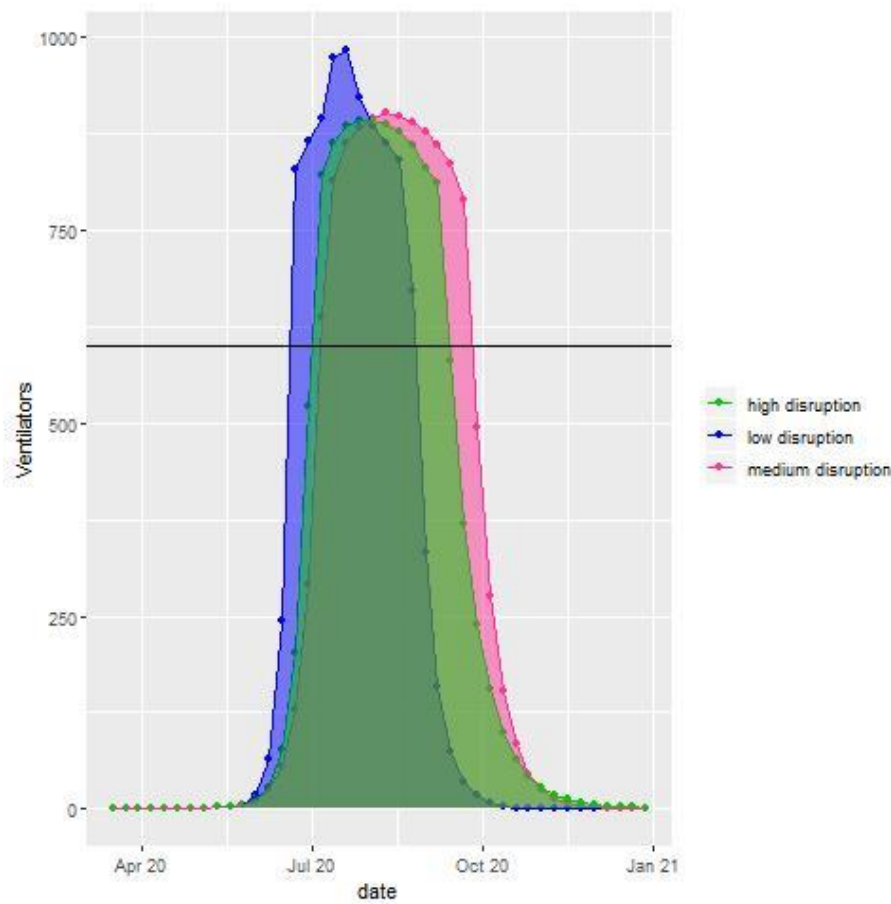


Figure 12: Predicted ventilator utilisation under different scenarios



4 Discussion

The GoN has been able to control the spread of COVID-19 through strict intervention packages including travel restrictions and social distancing measures that were introduced early in the epidemic. However, these interventions carry a huge socio-economic burden and might be unsustainable in the long run. We have explored various strategies of release from the current strict intervention measures using three different intervention packages.

We compared low, medium, and high disruption strategies, as described in Section 1.2. The model predicted that the high disruption strategy, which includes extending the self-isolation of suspected cases and quarantine of contacts and hand hygiene measures, was substantially more effective in decreasing the number of deaths and the burden on the healthcare system than any other disruption strategy. Indeed, the medium disruption strategy, which includes the extension of interventions like closing schools, limitation of imported cases, and hand hygiene measures, was found to be significantly less effective.

The significant difference between the impact of the high and medium disruption strategies may be attributed to the (assumed) effectiveness of the self-isolation and household quarantine of suspected cases measures. Under these strategies, we assumed a percentage of the people who currently live in the same house as a person who has tested positive for COVID-19 will voluntarily quarantine themselves at home for an average of 14 days, preventing them from travelling to work, school, or any other social gatherings. These interventions lead to a reduced rate of contact between infected and susceptible individuals, severely inhibiting the spread of the disease among the population. Other interventions considered in the medium disruption strategy, such as school closures, are not as effective as they do not sufficiently reduce the rate of contact between people (i.e. even though schools would be closed, the disease could spread through contacts at home, work, or other social gatherings) and hence provide multiple opportunities for the transmission of the disease between people in the population.

It is important to note that the high disruption strategy was highly sensitive to the level of adherence to and coverage of the interventions. In the analysis, we assumed there was medium coverage of and adherence to the self-quarantine measure (50% and 50% respectively) and low coverage of the quarantine of household contacts measure (20%). Estimation of the intervention parameters was made based on our collective experiences of working in Nepal, where we accounted for the pragmatic difficulties in implementing high coverage and adherence to these measures in the country context. However, strategies to increase the coverage of and adherence to these interventions would further decrease the incidence and deaths from the disease. This can include the increased identification of the reservoir of both symptomatic and asymptomatic cases by implementing enhanced testing protocols and strategies to enhance their isolation. This should in addition embrace the strategies for contact tracing and testing, while implementing strategies for their isolation and quarantine.

The model predicted that huge proportions of patients might die in the absence of proper treatment with the current health system capacity. A large number of untreated deaths predicted during the epidemic were due to the lack of ICU and ventilator treatment. The

model also predicted a need for around 5,000–11,000 surge ICU beds and around 400 surge ventilators to accommodate the treatment of serious cases during the epidemic. A pre-emptive preparation of healthcare capacity in terms of development of critical care facilities, adequately trained human resources, and personal protective equipment is required to deal with the epidemic.

The model compares the estimated COVID-19 deaths with the ongoing natural deaths in Nepal and estimates that around 19% of all-cause deaths would be attributed to COVID-19 by the end of the year under the high disruption strategy. Nepal's preparedness plan should also anticipate an additional large proportion of patients with other illnesses seeking healthcare from the already overwhelmed health system. The total number of deaths is estimated to be around 0.2% of the infected Nepali population (both symptomatic and asymptomatic) across all strategies, which is lower than the fatality rates reported from many high-income countries (15). This could be related to the population structure of Nepal, as the country has a relatively smaller population above the age of 60 years who are expected to have a high chance of suffering from severe illness and mortality, as well as to assumptions around the reporting of asymptomatic cases. However, this estimate does not consider the effect of various co-morbidities on the population, which are expected to be highly prevalent in Nepal (14).

The model predicts high incidence of total cases (a maximum reported incidence of 75,000 new cases per day under the low disruptive strategy, and a minimum reported incidence of 46,800 new cases per day under the high disruption strategy). These numbers should be interpreted in the light of various assumptions, including the assumption that the current reporting rate of symptomatic cases is 10% and that of asymptomatic cases is 5% based on the low reporting rates published from other settings. Uncertainty in the reporting rate of cases and even deaths is significant. Even countries with the most strict and aggressive testing policies have under-reported deaths. The City of Wuhan added 1,290 deaths due to COVID-19 when they revised their official estimates (16), bringing the official death total in China to 4,638. Similar issues of underreporting have been observed in other locations, including New York, which added 3,700 deaths from people suspected of having COVID-19 but who were never tested (17). As there is a lack of available data on the reporting rates in Nepal, we estimated these parameters using our knowledge and experience of working in the Nepali context.

As community testing is not widely implemented in Nepal, there is significant uncertainty around the unreported infections in the community. Additionally, the reporting rate of new cases is likely to be dependent on the health system's capacity. In reality, at the peak of the outbreak when the healthcare system is most likely to be over-stretched, it is plausible that a smaller fraction of cases will be tested, diagnosed, and reported. This observation is also likely for many other countries during the peak outbreak where only patients with severe cases seek hospital care and are likely to get reported.

The model from Imperial College London (18) predicts a peak infection prevalence of 2.6 million if no interventions are applied from now onwards (this is comparable to our low disruption scenario where the peak total incidence is 846,000 new cases per day). The Imperial model also predicts 370,000 cumulative deaths by the end of the year, which is significantly more than our model's prediction of 49,000 deaths in the low disruption scenario. It is not possible to sufficiently reproduce different intervention scenarios with other

currently available models as they operate with different model structures, assumptions, and output metrics. Furthermore, we have not performed a model comparison exercise between our model and the Imperial model as it is outside the scope of this work.

In addition to the above points, it is worth noting again that the results from the model will change as we learn more about the disease. Currently, Nepal is in the very early stages of the epidemic and little is known about the contextual host immunity factors and environmental factors that influence the transmission dynamics and mortality in Nepal. In addition to the inherent uncertainty of various parameters around the disease and intervention, various parameters used in the model were derived from the experience of other settings that might not truly represent the population and context of Nepal. However, the model is robust enough to take into account the important factors influencing the transmission dynamics and outcomes, and is expected to sufficiently predict the pattern of the epidemic and the outcome of cases.

5 Conclusion

5.1 Summary of key findings

We summarise the key findings of the different scenarios (low, medium, and high disruption strategies) in Table 2:

Table 2: Key findings by scenario

Parameters	Low disruption strategy	Medium disruption strategy	High disruption strategy
% of population infected with COVID-19 by end of year	81.1%	73.1%	64.8%
Peak to be reached at	Jun–Sep	Jul–Oct	Jun–Oct
Number of new cases per day at the peak	846,000	548,000	531,000
COVID-19 deaths	49,200	44,200	32,900
All-cause cumulative deaths by end of year	193,000	188,000	176,000
Number of deaths attributed to COVID-19 in all-cause mortality by end of year	45,000	35,000	31,000
% of deaths attributed to COVID-19 in all-cause mortality by end of year	25%	23%	19%
Number of ICU beds to be occupied	12,400	8,000	6,600
Number of ventilators to be used	1,000	1,000	1,000

These results indicate that:

- The disruption strategies discussed above show an increasing impact in the number of deaths averted, with the medium and high disruption strategies reducing the disease burden by 5,000 and 16,300 deaths, respectively, relative to the low disruption strategy, which is the current strategy.
- We recognise, however, that the medium and high disruption strategies would present increasing orders of disruption to people’s lives, potentially having significant social and economic repercussions.
- We anticipate there will be significant demand for ICU beds and ventilators to treat severe COVID-19 cases. However, over-utilisation of hospital equipment will be eased if the high disruption strategy is implemented.

5.2 Significance of these findings

Based on the results described above, with the caveat of significant uncertainties, we anticipate that the high disruption scenario is likely to avert a significant number of COVID-19 related deaths. This strategy is also most likely to minimise the stress on the healthcare system. However, the strategy's economic implications and indirect effects on excess mortality could be significant.

It is worth noting that COVID-19 is transmitted through person-to-person contact. Reducing social contact between people is essential in containing the outbreak of the disease and is the primary reason why the high disruption strategy is so effective. It should be emphasised that people who do not show visible symptoms of the disease may still be infected as they may be asymptomatic but still infectious. For this reason, we recommend that individuals avoid social gatherings that are not deemed essential, as this will undoubtedly have positive benefits.

Further analysis of the modelling and the data could reveal important and additional insights on some of the detailed and complex policy questions, as is outlined in the next section. It is also important to understand the economic impact of each of these interventions and plan a holistic health system-wide response involving the health workforce, hospital capacity, equipment, supply chains, etc.

5.3 Further analysis of the modelling

This report has been produced in a very short timeline and the scope has been limited to answering the preliminary questions on what would be the likely incidence and mortality if there is no intervention and answering the same for the most feasible intervention. Further analysis could include some of the topics listed below:

1. Conducting similar analyses as described in this report at a sub-national level.
 - Such an analysis would allow policymakers to develop policies specific to each region, as well as identify areas that are likely to experience the highest burden in the hospital system.
2. Conducting a sensitivity analysis at the national level, assessing the sensitivity of the results to variations in the model parameters.
 - In this report, we have stressed the sensitivity of the results to uncertainty in the model parameters; a sensitivity analysis would allow us to assess the extent of the uncertainty in a quantitative manner.
3. Assessing the economic impact of the burden of the disease and the various strategies enacted by the GoN.
 - Given the vulnerability of the population of Nepal, it is important to assess the economic impact of the disease as well as the intervention strategies, ensuring they are effective but also economically viable.
4. Assessing the impact of co-morbidities on disease mortality:

- Adjusting the disease mortality rate for specific co-morbidities.
 - This would require knowing the percent of the population that have each type of co-morbidity, preferably disaggregated by age.
5. Analysing the effect of a time-dependent force of infection to model seasonal changes.
- It should be noted that given the limited evidence in the relation between climate variability and COVID-19, it is likely that such an analysis will include significant degrees of uncertainty.

We also recommend using additional evidence from other public health, social protection, and economic analyses to ensure that the policy decisions are made using evidence that is context specific and applicable.

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Annex A Terms of Reference

Introduction

1. The Department for International Development (DFID) is the part of the UK government that manages Britain's aid to low-income countries and works to eradicate extreme poverty. DFID is working with others to reach the Sustainable Development Goals (SDGs) by 2030.
2. The Research and Evidence Division (RED) within DFID leads on the generation of new evidence through research and evaluation to improve the effectiveness and efficiency of development interventions aimed at eliminating poverty and reducing vulnerability. RED provides this support in four broad areas:
 - a. Generating evidence on need and context, enabling decision-makers to better understand the changing nature of the environment in which they are working and to plan for the future;
 - b. Supporting evidence on "what works", enabling decision-makers to invest in interventions that are most likely to work;
 - c. Facilitating the better use of existing evidence ensuring that decision-makers can access high-quality, relevant information when they need it; and
 - d. Supporting the capacity building of Southern research organisations, enabling the development of nationally owned research agendas.
3. The South Asia Research Hub (SARH) is a decentralised team based in Delhi with a geographical focus on Afghanistan, Bangladesh, Burma, India, Nepal and Pakistan. SARH supports research on emerging issues that have cross-border relevance or are common to multiple countries in South Asia.
4. The following Terms of Reference (ToRs) sets out the requirements for the UK Department for International Development (DFID) funded research study into ***"Modelling of Covid-19 Scenarios in"***.

Background

Covid-19 started towards the end of 2019 and early 2020 in Wuhan, China. It was a cluster of pneumonia cases of which the cause was not known. It has since been found that the cause of the pneumonia is the novel virus SARS-coV-2 which causes the disease COVID-19. Covid-19 has been declared as a pandemic by the World Health Organisation (WHO). WHO states that about 80% of people with Covid-19 recover without needing specialist treatment and that about one person in every six becomes seriously ill and develops difficulty breathing. This is not the first outbreak of disease in China. SARS also broke out in China but was largely contained.

In Nepal the Ministry of Health and Population, Government of Nepal is providing daily Situation Reports (SITREPs) on the Covid-19 situation from the Health Emergency and Disaster Management Unit. These are updated on a daily basis.

https://heoc.mohp.gov.np/update-on-novel-corona-virus-2019_ncov/

As of today (07 APRIL 2020), the number of confirmed cases in Nepal is six. One case of transmission within Nepal has been reported and Nepal has moved to stage 2. The local response is focused on hospital preparedness and increasing checks and controls at immigration.

Scope

Use an existing SEIR model (e.g. <https://neherlab.org/covid19/>, Imperial's model, or a similar credible model) to run a large series of simulations for the likely spread of Covid-19 in Nepal and its impact on hospital and ICU capacity over the next two years. This should also take into account factors such as the effect/impact of social distancing, hand washing practised and lockdown if possible.

We would also want from a model or analysis to be able to identify where to invest in services where not enough service provision is available such as slums in urban areas or on the Terai and mountains. There is data on services and access but need to present that data in a way that is useable by Government of Nepal (GoN) and other partners.

Outputs of the model should indicate the size and date of peaks under different assumptions, with sensitivity analysis, by palika (if possible), province and nationally. The team should identify if it is possible for the model to allow for Nepal's varied demography (in terms of age, household size, household membership, co-morbidity, migration patterns and social networks, and likely imports of the disease). DFID Partners should be able to provide data inputs on this and this analysis will be done should data and time allow.

A range of different assumptions for R_0 , proportion of the population susceptible, percent of hospitalisations, critical care and fatalities by age and co-morbidity group, mitigation and suppression measures for example should be used. We have a partner who can potentially help with input from previous collected data sources.

Data on Covid-19 cases, demography, co-morbidity, and health facilities are available from the Ministry of Health and associated websites and surveys including the DHS (2016). If possible and realistic the team should explore the use of novel social media derived datasets to provide real time updates to modelled population figures.

Outputs

The outputs would be in the form of a series of graphs for different geographies and different assumptions and accompanying notes. The team would also provide the full code (with the caveat that this is not commercially produced code and so documentation will be minimal and updates unavailable unless by request), any associated workings, raw data tables for consumption by others for reuse in dashboards re-visualising data for example.

The team would also feed into discussions with the DFID Nepal team to consider where best to target limited resources in Nepal. The team should be able to produce outputs in a way that they can be used to easily communicate with Government of Nepal counterparts.

In time, the team may be asked to support extending the model to cover potential costs of different scenarios, and to provide additional explanation of their work.

Timeline

This is urgent.

- Ideally an outline report with a description of the model and initial results (without intervention) be produced by 15 April 2020.
- As soon as possible that team should hold a conversation with the World Bank identified lead in Nepal who has access to relevant data sets that will contextualise the model.
- 22 April submit full model and add parameters and produce results in different scenarios.
- Following submission of the second report meet with DFID Nepal do discuss development of dashboards, costing work and maps.

Management Arrangements

5. Clearly given the objective of this work, management arrangements are critical. We would need to understand if potential suppliers are able to complete this work within the tight line on a sensitive topic.

Project Team

6. The proposed team should have the following skills, experience, and qualifications:
 - a) Demonstrated ability to work at pace and deliver excellent products within tight timescales.
 - b) Managing and undertaking rigorous data modelling.
 - c) Demonstrated ability to communicate complex information to non-specialists in easy to use formats.

Budget

- a) **Please indicate cost on number of hours input against framework agreed rates.**

Call schedule:

- a) Issue of call for Proposals to suppliers: **07 April 2020**
- b) Deadline for submission of full proposals: **09 April 2020**
- c) Commence research at the latest: **10 April 2020**

Data Management

39. The supplier will be expected to set out how they will manage the data from the research given its transfer from one supplier to another insuring compliance with legal requirements.

Bidding process

1. The technical proposal (up to 2 pages; Arial 11 or similar) should provide information on how the work will be completed, team skills and experience – both on modelling and communicating and proposed team composition. The technical proposal should include a work plan and a learning and communications plan (the communications

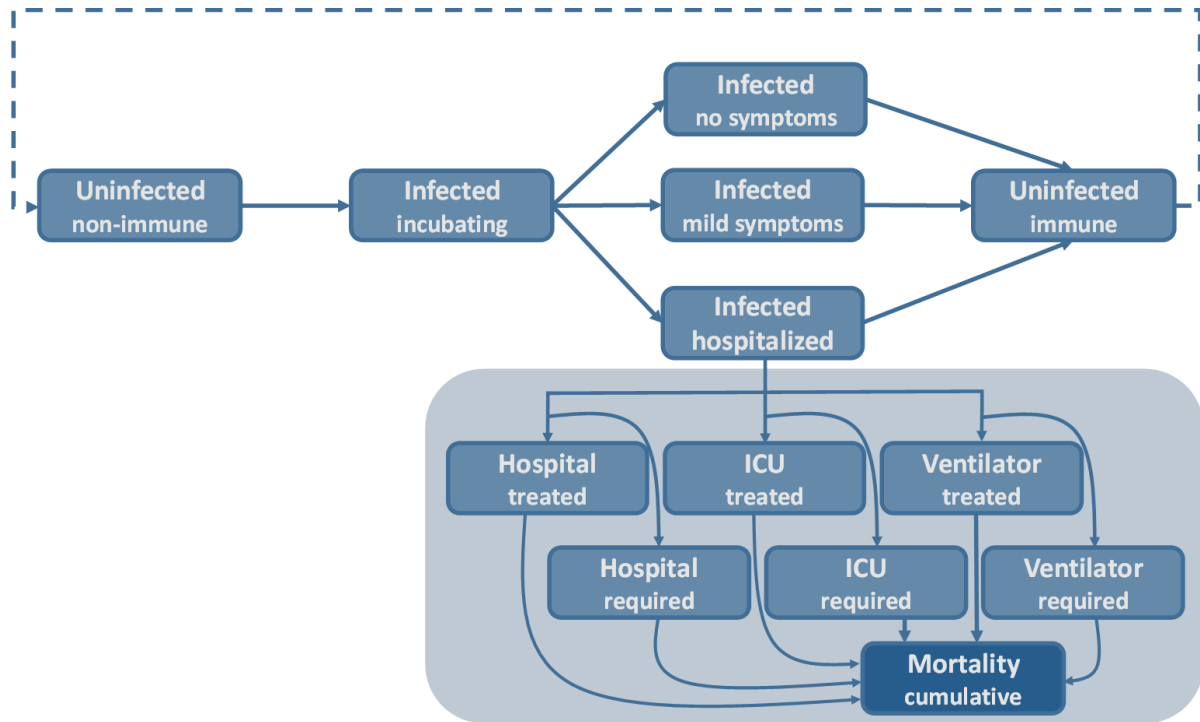
plan can be annexed). Detailed CVs should be annexed (not to be counted within the 12 pages).

2. The commercial proposal should clearly disaggregate the budget.

Annex B Model description

An age-structured SEIR (susceptible-exposed-infected-recovered) model with the 'infected' compartments stratified by symptoms, severity, and treatment seeking and access.

Figure 13: Diagram of the baseline model structure including both age-structured epidemiological and healthcare utilisation components



The baseline model structure is illustrated in Figure 13, with model equations given by Equation 1. The baseline represents the scenario of unmitigated spread of infection in the absence of NPIs. The age structure is informed by data on population numbers, births, and deaths by age (8). Contact matrices estimating the number of daily contacts between age groups stratified by location (home, work, school, other) were used to inform age-dependent transmission (9).

$$\frac{dS}{dt} = -S \circ \Lambda + \omega R + A \cdot S - \mu \cdot S + bP \quad (1)$$

$$\frac{dE}{dt} = S \circ \Lambda - \gamma E + A \cdot E - \mu \cdot E$$

$$\frac{dI}{dt} = \gamma (1 - p_{clin})(1 - p_{ihr}) \cdot E - \nu_I I + A \cdot I - \mu \cdot I$$

$$\frac{dC}{dt} = \gamma p_{clin}(1 - p_{ihr}) \cdot E - \nu_I C + A \cdot C - \mu \cdot C$$

$$\begin{aligned} \frac{dR}{dt} = & v_I(I + C) + A \cdot R - \omega R - \mu \cdot R + (1 - \delta_H p_{hfr})v_H \cdot H + (1 - \delta_{H_c} p_{hfr})v_H \cdot H_c \\ & + (1 - \delta_U p_{hfr})v_U \cdot U + (1 - \delta_{U_c} p_{hfr})v_U \cdot U_c + (1 - \delta_{V_c} p_{hfr})v_V \cdot U_{cv} \\ & + (1 - \delta_V p_{hfr})v_V \cdot V + (1 - \delta_{V_c} p_{hfr})v_V \cdot V_c \end{aligned}$$

$$\frac{dH}{dt} = p_{ihr}(1 - p_U)(1 - p_{K_H})\gamma E - v_H H + A \cdot H - \mu \cdot H$$

$$\frac{dH_c}{dt} = p_{ihr}(1 - p_U)p_{K_H}\gamma E - v_H H_c + A \cdot H_c - \mu \cdot H_c$$

$$\frac{dU}{dt} = p_{ihr}p_U(1 - p_{K_U})(1 - p_V)\gamma E - v_U U + A \cdot U - \mu \cdot U$$

$$\frac{dU_c}{dt} = p_{ihr}p_U p_{K_U}(1 - p_V)\gamma E - v_U U_c + A \cdot U_c - \mu \cdot U_c$$

$$\frac{dU_{cv}}{dt} = p_{ihr}p_U p_{K_U} p_V \gamma E - v_U U_{cv} + A \cdot U_{cv} - \mu \cdot U_{cv}$$

$$\frac{dV}{dt} = p_{ihr}p_U(1 - p_{K_U})(1 - p_{K_V})p_V \gamma E - v_V V + A \cdot V - \mu \cdot V$$

$$\frac{dV_c}{dt} = p_{ihr}p_U(1 - p_{K_U})p_{K_V} p_V \gamma E - v_V V_c + A \cdot V_c - \mu \cdot V_c$$

$$P = (S + E + I + C + R + H + H_c + U + U_c + U_{cv} + V + V_c)$$

$$s = 1 + a \cos \left(2\pi \frac{\left(t - \left(\frac{365.25\phi}{12} \right) + t_{in} \right)}{365.25} \right)$$

$$W = W_{home} + W_{work} + W_{school} + W_{other}$$

$$\Lambda = p s W \cdot \left(\frac{\rho E + I + C + \rho_s * (H + H_c + U + U_c + U_{cv} + V + V_c)}{P} \right)$$

$$A = \begin{pmatrix} \begin{pmatrix} -\alpha & 0 \\ \alpha & -\alpha \end{pmatrix} & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & \begin{pmatrix} -\alpha & 0 \\ \alpha & 0 \end{pmatrix} \end{pmatrix}$$

$$p_{K_H} = \begin{cases} 0 & \text{for } H < K_H \\ 1 & \text{for } H \geq K_H \end{cases}$$

$$p_{K_U} = \begin{cases} 0 & \text{for } U < K_U \\ 1 & \text{for } U \geq K_U \end{cases}$$

$$p_{K_V} = \begin{cases} 0 & \text{for } V < K_V \\ 1 & \text{for } V \geq K_V \end{cases}$$

Table 3: Description of the model variables

Symbol	Definition
S	Susceptible
E	Infected and incubating
I	Infectious and asymptomatic following incubation
C	Infectious and mildly symptomatic following incubation
R	Recovered and immune
H	Severe infection: hospitalised
H _c	Severe infection: not hospitalised due to lack of capacity
U	Severe infection: hospitalised in ICU
U _c	Severe infection: hospitalised and requiring ICU but placed in surge ward
U _{cv}	Severe infection: hospitalised and requiring ventilator but placed in surge ward
V	Severe infection: hospitalised in ICU and on a ventilator
V _c	Severe infection: hospitalised in ICU requiring a ventilator but not on one

Table 4: List of the default parameter values used

Symbol	Definition	Value	Unit	Source
Demographic data				
W_{home}	Country-specific age-dependent contact matrix describing the number of potentially infectious contacts at home per person per day	†	day-1	(9)
W_{work}	Country-specific age-dependent contact matrix describing the number of potentially infectious contacts at work per person per day	†	day-1	(9)
W_{school}	Country-specific age-dependent contact matrix describing the number of potentially infectious contacts at school per person per day	†	day-1	(9)
W_{other}	Country-specific age-dependent contact matrix describing the number of potentially infectious societal contacts per person per day	†	day-1	(9)
μ	1/Age-dependent non-COVID related death rate	†	days	(8)
b	1/ Age-dependent fertility rate	†	days	(8)
α	Ageing rate between age categories	0.2	year-1	
Natural history of infection				
p	Probability of infection given a single contact	†	NA	(20)
γ	1/duration of incubation period	3.5	days	(21–23)
ρ	Relative infectiousness of incubating phase	0.1	NA	‡

Symbol	Definition	Value	Unit	Source
p_{clin}	Proportion of all infections that ever develop symptoms	0.55	NA	(24,25)
ν_I	1/duration of infectious phase post incubation	4.5	days	(21)
ρ_s	Relative proportion of contacts for hospitalised patients	0.15	NA	†
ω	1/duration of immunity	150	years	†
Seasonality				
a	Relative variation in viral transmissibility throughout the year (+- a proportion)	0	NA	-
ϕ	Month of peak in transmissibility	-	NA	-
Patient outcomes				
p_{ihr}	Probability of an infection being severe (requiring hospitalisation) by age		NA	(10,19,26)
p_{hfr}	Probability of a severe/hospitalised infection being fatal by age		NA	(10,19)
ν_H	1/Duration of hospitalised infection	24	days	(27)
ν_U	1/Duration of ICU infection	24	days	(23,28)
ν_V	1/Duration of ventilated infection	24	days	(21,22)
δ_H	Maximum probability of death for a hospitalised infection	0.35		(19,27)
δ_{Hc}	Maximum probability of death for an infection requiring hospitalisation that did not receive appropriate treatment	0.45	NA	(29)
δ_U	Maximum probability of death for a hospitalised infection requiring ICU admission	0.55	NA	(29,30)
δ_{Uc}	Maximum probability of death for a hospitalised infection that would require ICU admission but was not admitted to the ICU	0.8	NA	(29)
δ_V	Maximum probability of death for a hospitalised infection requiring a ventilator	0.8	NA	(29)
δ_{Vc}	Maximum probability of death for a hospitalised infection that would require a ventilator but did not get one	0.95	NA	(31)
p_U	Probability of an infected patient needing ICU	0.5	NA	(26,31)
p_V	Probability of an infected patient needing ICU and a ventilator	0.75	NA	(31)
K_H	Standard hospital bed capacity	26,930	NA	(12)
K_U	ICU bed capacity	1595	NA	(12)
K_V	Ventilator capacity	600	NA	(12)

These are subject to change when the model is applied to a new setting and/or with new incoming information. We have provided references to demonstrate that the default values lie within plausible ranges.

† Country-specific value

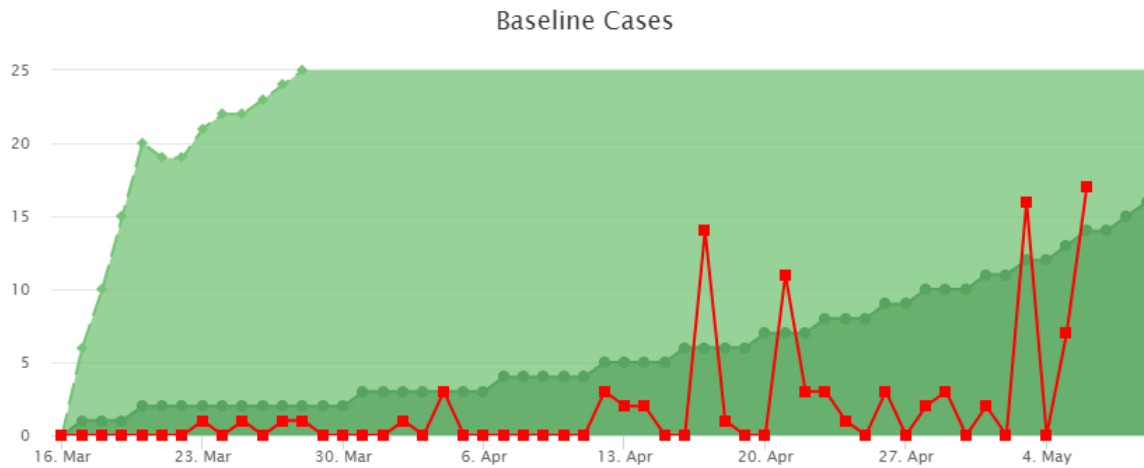
‡ Assumed value (no reference found)

Annex C Model calibration

Focus on:

 Observed
 Predicted Reported
 Predicted Reported + Unreported

3.76 days ²
to double the number of
infections at inception.



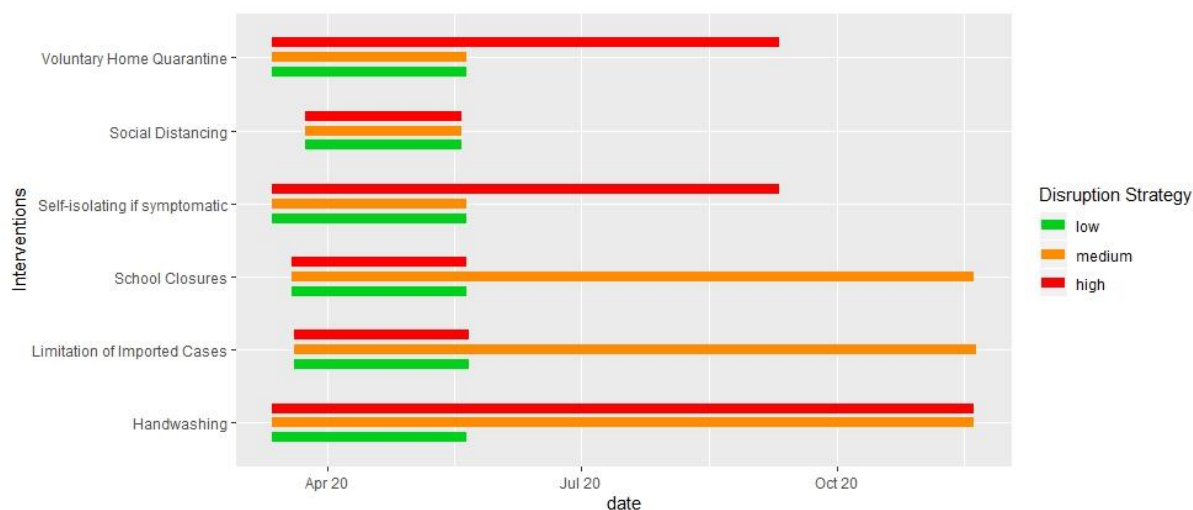
The model was calibrated with the assumption that 5%, 10%, and 100% of all asymptomatic cases, symptomatic cases, and hospitalised cases respectively were reported to the health systems; the current intervention has the coverage and adherence as described in Annex D and the probably of infection given a contact with an infected person is 0.025 in Nepal.

Annex D Description of disruption strategies

Scenario 1: Low disruption strategy

All the interventions are removed after 8 to 10 weeks of introduction as the current package of interventions ends on 18 May

- **Self-isolation if symptomatic**
 - Start date: 12 March 2020
 - Duration: 10 weeks
 - Coverage: 50%
 - Adherence: 50%
- **Social distancing**
 - Start date: 24 March 2020
 - Duration: 8 weeks
 - Coverage: 70%
 - Adherence: 70%
- **Handwashing**
 - Start date: 12 March 2020
 - Duration: 10 weeks
 - Efficacy: 10%
- **School closures**
 - Start date: 19 March 2020
 - Duration: 9 weeks
 - Efficacy: 85%
 - Home contacts inflation: 20%
- **Limitation of imported cases**
 - Start date: 20 March 2020
 - Duration: 9 weeks
 - Efficacy: 90%
- **Voluntary home quarantine**
 - Start date: 12 March 2020
 - Duration: 10 weeks
 - Days in isolation for average person: 14 days
 - Coverage: 20%
 - Decrease in the number of other contacts: 20%
 - Increase in number of contacts at home: 100%

Figure 14: Intervention packages with current interventions**Scenario 2: Medium disruption strategy**

Handwashing, school closure, and limitation of imported cases for an additional 26 weeks after the other intervention packages are over. Other interventions – i.e. social distancing, self-isolation if symptomatic, and voluntary home quarantine – that started at the dates mentioned in scenario 1 end on 19 to 22 May 2020.

- **Handwashing**
 - Start date: 12 March 2020
 - Duration: 10 weeks + 26 weeks = 36 weeks
 - Efficacy: 10%
- **School closures**
 - Start date: 19 March 2020
 - Duration: 9 weeks + 26 weeks = 35 weeks
 - Efficacy: 85%
 - Home Contacts Inflation: 20%
- **Limitation of imported cases**
 - Start date: 20 March 2020
 - Duration: 9 weeks + 26 weeks = 35 weeks
 - Efficacy: 50%

Scenario 3: High disruption strategy

This refers to keeping in place self-isolation if symptomatic and voluntary quarantine for an additional 16 weeks and hand washing for an additional 26 weeks after the release of the other intervention packages. Other interventions – i.e. social distancing, school closures, and limitation of imported cases – that started at the dates mentioned in scenario 1 end between 19 and 22 May 2020.

- **Self-isolation if symptomatic**

- Start date: 12 March 2020
- Duration: 10 weeks + 16 weeks = 26 weeks
- Coverage: 50%
- Adherence: 50%
- **Handwashing**
 - Start date: 12 March 2020
 - Duration: 10 weeks + 26 weeks = 36 weeks
 - Efficacy: 5%
- **Voluntary home quarantine**
 - Start date: 12 March 2020
 - Duration: 10 weeks + 16 weeks = 26 weeks
 - Days in isolation for average person: 14 days
 - Coverage: 20%
 - Decrease in the number of other contacts: 20%
 - Increase in number of contacts at home: 100%

Annex E Description of interventions

A series of NPIs, which can be delivered for specific periods of time, were included in the model structure.

Self-isolation if symptomatic

This is the practice of individuals with either a confirmed case of COVID-19 or with COVID-19 symptoms isolating themselves at home for a period of seven days. The parameters governing this intervention are:

- Start date: the start date of the protocol
- Duration: the duration of the protocol
- Coverage: the percentage of the population who will be able to self-isolate if they have symptoms or are a confirmed case
- Adherence: the percentage of the designated isolation period that self-isolated individuals adhere to the intervention
- Screening: an additional screening approach in addition to individuals who report. This could be a form of contact-tracing screening for symptoms or the disease using a diagnostic test. All individuals with symptoms or a confirmed case are then requested to self-isolate
- Screening/Start date: the start date of additional screening
- Screening/Coverage: the expected additional percentage of infected people who could be found through contact tracing / additional screening
- Screening/Duration: duration of this additional protocol

Social distancing

Also known as physical distancing, this refers to the measures taken to prevent the spread of a contagious disease by maintaining a specific physical distance between individuals and reducing the number of times that individuals come into close contact with each other. Under this intervention, it assumes a proportion of all travel (that is not related to work or school) or any type of social gatherings is banned. The parameters governing this intervention are:

- Start date: the start date of the protocol
- Duration: the duration of the protocol
- Coverage: the percentage of the population who reduce their societal contacts (excluding those at home, work, and school)
- Adherence: the percentage of the time that those practising social distancing adhere to social distancing measures

Handwashing

This intervention assumes the general population will improve their personal hygiene and reduce risky behaviours (e.g. touching the face, nose, or mouth). Personal hygiene interventions could include (but are not limited to) frequently washing hands with soapy

water following the WHO guidelines,² wearing a mask when out in public, and covering coughs and sneezes. The parameters governing this intervention are:

- Start date: the start date of the protocol
- Duration: the duration of the protocol
- Efficacy: the effectiveness of hand hygiene measures in reducing the risk of infection per contact

Working at home

This intervention assumes a proportion of the workforce work from home. This will allow people to continue their work, while avoiding contacts in the workplace. The parameters governing this intervention are:

- Start date: the start date of the protocol
- Duration: the duration of the protocol
- Efficacy: the reduction in work-related contacts
- Home contacts inflation: increased numbers of home contacts due to increased numbers of individuals working from home

School closures

This intervention assumes a proportion of all schools are closed. When schools are closed, children are assumed to remain at home and therefore increase their contacts at home. The parameters governing this intervention are:

- Start date: the start date of the protocol
- Duration: the duration of the protocol
- Efficacy: defined as the reduction in contacts between schoolchildren when schools are closed
- Home contacts inflation: increased numbers of home contacts due to increased numbers of children at home

Cocooning the elderly

This intervention is designed to isolate a proportion of the elderly population, above a certain age, and reduce their overall contacts. This effectively isolates the elderly population, regardless of whether they have the disease or not. The parameters governing this intervention are:

- Start date: the start date of the protocol
- Duration: the duration of the protocol
- Coverage: the percentage of the elderly population who are cocooned
- Efficacy: defined as the reduction in overall contacts of the cocooned elderly population
- Minimum age for elderly cocoon: the minimum age cut-off at which elderly people should cocoon themselves

² www.who.int/gpsc/clean_hands_protection/en/

Limitation of imported cases

This refers to a ban on international travel, including flights into and out of the country, as well as people crossing international borders. The parameters governing this intervention are:

- Start date: the start date of the protocol
- Duration: the duration of the protocol
- Efficacy: the reduction in imported cases per day (as a percentage)

Voluntary home quarantine

This indicates how many people will voluntarily quarantine themselves at home for a specified number of days if a person they live with tests positive for COVID-19. The parameters governing this intervention are:

- Start date: the start date of the protocol
- Duration: the duration of the protocol
- Days in quarantine for an average person
- Coverage: the percentage of people voluntarily quarantining themselves
- Decrease in the number of other contacts when voluntarily quarantining: refers to decreased numbers of contacts outside of the home due to increased numbers of individuals voluntarily quarantining themselves
- Increase in the number of contacts at home when voluntarily quarantining: refers to increased numbers of home contacts due to increased numbers of individuals voluntarily quarantining themselves