COVID-19 vaccine delivery in LMICs: How to think about concentration vs dispersion in delivery?

Authors: Sid Rupani, Senior Director Global Impact Team, Coupa; Aaron Thomas, Solution Architect, Coupa; Wendy Prosser, Senior Technical Officer, John Snow Inc. (JSI); Dr. Ahmadu Yakubu, Senior Advisor Health, UNICEF; Dr. Mariam Zameer, Senior Manager Health Systems, VillageReach

Executive Summary:

COVID-19 vaccine delivery has begun in many low- and middle- income countries (LMICs) and many countries will be looking to scale as more vaccines arrive. The distribution of COVID-19 vaccines is distinct due to limited vaccine availability, different target populations compared to routine immunizations, and the importance of speed in reaching the maximum number of people, driving the need to explore alternative delivery and supply chain designs. This report investigates the question: **How concentrated or dispersed should COVID vaccination delivery be** in different geographic areas and with varying available vaccine supply? Should COVID-19 vaccines be delivered through a few large, centralized vaccination locations (*concentrated*) or through many small vaccination locations closer to target populations (*dispersed*)? The report also explores how delivery strategy changes with vaccine allocation and throughput to reach full population coverage, target vulnerable populations, and minimize cost.

Network optimization modeling of a sample representative LMIC is used to provide COVID-19 vaccine delivery guidance for LMICs. The cost estimates should only be used for strategic discussion and direction on vaccine delivery. Recommendations are provided on

- vaccination location concentration,
- mass vaccination site potential,
- health workforce requirements, and
- budgeting to target vulnerable populations and reduce access distance.

Vaccination location:

- Not all health facilities (HFs) need to administer COVID-19 vaccines
- At low levels of vaccine availability (e.g., 1% of the population per month), vaccination should be concentrated in 5-20% of HFs in largely urban areas and for the most vulnerable populations. As supply increases (e.g., 7% of the population per month), more vaccination locations (20%-45% of HF) should be opened.
- Rural regions with dispersed communities should consider opening up to 55% of HFs so that people do not have to travel more than 15 km to access vaccines. Additional outreach vaccination locations can be considered for remote populations.

Mass vaccination sites:

- Mass vaccination sites will play a niche role in overall delivery, even when vaccinating large numbers of people per month (throughput).
- To vaccinate 7% of the population per month, countries may consider 1-5 mass vaccination sites (administering >1,000 doses per day) in urban areas with over 3 million people and 3000 people/sq km. These sites would require at least 10 dedicated full-time

vaccinator teams. Mass vaccination sites are not required for rural areas or areas in cities with less than 500,000 population.
- If a country has sufficient supply to vaccinate 20% of the population per month, it can plan for 10-30% of its sites to be mass vaccination locations, but the mass vaccination sites in urban districts would still deliver only a minority of total doses being delivered in the country.

Health workforce:

- In regions with population density of 100+ people/sq km, at least one full-time COVID-19 vaccinator team is needed at 70% of vaccination sites to immunize 85%-95% of the target population. Urban districts should plan for dedicated full time vaccinator teams even at low vaccination throughput levels.
- In rural regions, at low vaccination throughputs (<3% of the population monthly), 50-70% of COVID-19 vaccination sites will require a team working part time (1-3 days a week) on COVID-19 vaccination while remaining sites need full time teams. At higher throughput levels (7% of the population monthly), only 30-50% of vaccination sites would have sufficient throughput with part time immunization teams. Vaccinator teams would either need to be hired, or health workers would reallocate time from routine health services to COVID-19 immunization.

Reaching the most vulnerable populations efficiently:

- Vulnerability driven allocation has only a marginal cost increase while addressing those at risk as recommended in SAGE guidelines. Opening vaccine sites based only on cost efficiency leads to immunization centered largely in urban areas and would only reduce delivery costs by 20%. Distributing vaccines by region in proportion to population is not recommended, as it is not only more costly but also does not specifically target the most vulnerable populations.
- Countries should consider the maximum distance people would travel to access a COVID-19 vaccine. In a scenario with a maximum distance constraint of 15km traveled by vaccine recipients, the increase in delivery cost per dose ranged from 12%to 36% over the scenario prioritizing cost efficiency. The greatest cost increase was in low throughput scenarios. Opening additional vaccination sites or mobile/outreach could be used to reduce the distance traveled by vaccinees.

Context

COVID-19 vaccine delivery has begun in many low- and middle-income countries (LMICs) and many will be looking to scale distribution as more vaccines arrive. Achieving country vaccination targets will require vaccinating a large proportion (>50% for most country targets) of populations. Countries aim to:

- vaccinate a high proportion of their populations as quickly as possible,
- ensure that vaccines reach high-impact and high-vulnerability target populations equitably,
- deliver vaccination at minimum cost, and
- work within existing human resource and infrastructure constraints.

Rolling out a COVID-19 vaccine has many distinct features compared to providing routine immunization or conducting a campaign for other vaccines. Some of the distinct features of COVID-19 vaccine rollout are:

- limited vaccine availability due to supply constraints,
- different target populations (e.g. health care workers, high risk groups, adults) and target population sizes,
- speed of reaching a large share of the population in a short period of time, and
- heighted safety requirements (e.g. use of PPE, social distancing) in vaccine administration.

These distinct factors drive the need to explore alternate delivery and supply chain designs.

Focus Questions

An important question about the delivery and supply chain design that countries will need to answer is: **how concentrated or dispersed should delivery be?** Should COVID-19 vaccines be delivered through a few large, centralized vaccination locations (*concentrated*) or through many small vaccination locations closer to target populations (*dispersed*)?

Further, how does the right level of concentration vs dispersion vary:

- for different geographic areas of the country (e.g. for geographically large, sparse, rural regions vs small, dense, urban regions),
- and as the available vaccine supply and the associated speed of vaccination (i.e. daily number of vaccine doses administered) changes?

This document provides guidance to answer these questions.

Approach

Network optimization[1] modeling is used to address the above question calibrated for a sample representative country. This country has population, population density, health facility density, population per health facility, that is close to the median across 77 COVAX Advanced Market Commitment (AMC) countries[2] that had public data available and also has representative variation in all the above dimensions. The country we use as a representative example has a population of approximately 20 million, approximately 3000 health facilities (HFs), about 7000 population per health facility, and a population density of 30 people per square kilometer.

The model is for strategic insight and should not be used for specific guidance for any specific country, but rather for understanding the trade-offs of different delivery models (concentrated vs. dispersed delivery) and the factors that drive it.

We focus our analysis on the delivery and supply chain distribution system within countries only, not on vaccine procurement and supply incoming to countries. The model includes COVID-19 vaccines that require standard refrigeration of 2C - 8C only, as these account for a very large share of vaccines to be delivered in LMICs (not vaccines which require storage in freezers or at ultracold temperatures).

We operationally define concentration vs. dispersion as **the number of vaccination locations as a fraction of the number of health facilities in rural and urban areas**. Mobile/outreach locations in addition to existing health facilities should also be considered but are not reflected in the results of the current model. The outputs of the model are:

- number of vaccination locations
- throughput of each vaccination location (in expected vaccinations per day) and vaccination team utilization,
- the distance that targeted populations would have to travel to vaccination locations (a measure of access),
- vaccination coverage, or the proportion of target population that is vaccinated in different locations, and
- average vaccination costs per dose for different scenarios

The objectives for the network optimization model are to obtain maximum coverage, especially of vulnerable populations, at a minimum cost.

Several scenarios are run to explore how answers vary with:

- Different levels of available vaccine supply and the associated throughput (i.e. daily number of vaccine doses administered).

[1] Network optimization is the process by which the optimal network structure, flows, and policies for any given set of sites, customers, products, demand (customer or site), sourcing policies, transportation policies, production policies, and inventory policies is determined via minimizing cost, maximizing profit, or considering a trade-off of various objectives according to Coupa Supply Chain.

[2] These are lower-income economies that will receive COVID-19 vaccines through COVAX AMC, funded largely through Official Development Assistance (ODA), as well as contributions from the private sector and philanthropy.

- Different vaccine allocation choices for the country, e.g., allow focus on only some regions or provinces, allocate vaccine doses to all regions or provinces in proportion to their population.

Additionally, we also conduct sensitivity analysis by varying the value of input assumptions.

The models do not optimize for maximizing vaccination throughput. Rather, the effect of throughput is explored in the scenarios. We assume that overall vaccination throughput in a country (in terms of daily number of vaccine doses administered) will be constrained by available supply. We look at how the optimal levels of concentration vs dispersion (i.e., HF% usage) vary at different levels of available vaccine supply and associated vaccine delivery speed. In reality, it is possible that throughput in a country will be constrained by factors other than available supply (e.g., vaccine hesitancy). However, as our goal is to provide guidance to countries, we tailor that guidance to address the design of a delivery system that uses all available vaccine supply.

When exploring vaccination allocation strategy, targeting high impact populations is considered by referencing the Africa COVID Community Vulnerability Index (CCVI) from the Surgo Foundation. The CCVI considers the factors: age, epidemiological, fragility, health system, population density, socioeconomic, and transportation availability and housing to measure COVID population vulnerability. Regional vulnerability indexes are used as an incentive for the model to target high impact populations. Higher vulnerability indexes indicate more at-risk populations. The country of study has an overall CCVI between 0.2 and 0.3, compared to its continent, with provincial indexes ranging from 0.05 to 0.80.

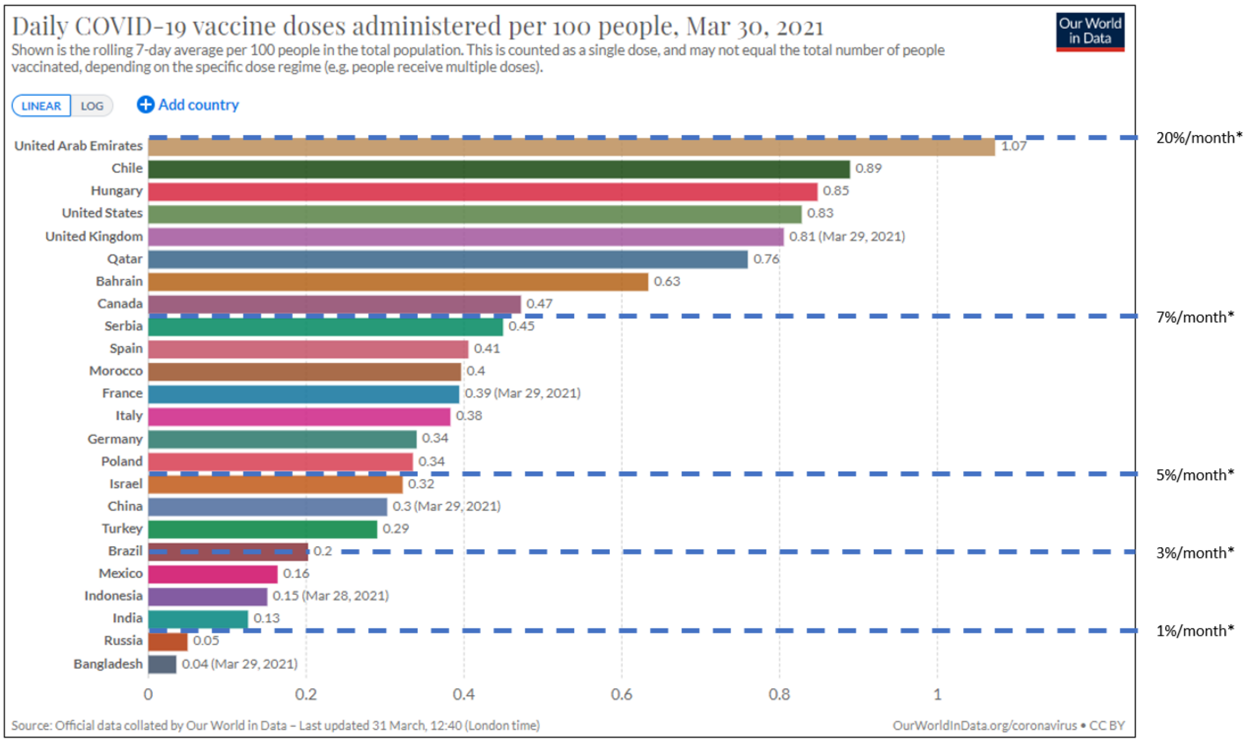
Input Assumptions

Vaccination throughput levels are defined by looking at available supply as a fraction of total populations and seeing how those change over time. We look at the COVAX global supply forecast and additional doses procured by the African Union as our indication of supply levels over time. We then divide by the total population of all countries covered by COVAX. With that approach we obtain the following indicative levels. These are not meant to be exact throughputs but are meant to illustrate the range of different rates of vaccination as supply scales over time.

Vaccination Throughput Level	Value
Level 1 (indicative of early supply phase e.g. first 3 months)	1% of population (two doses) per month, which is approximately 15,000 doses per day in this model, and will take 100 months to vaccinate everyone
Level 2 (indicative of next 3 months as supply increases)	3% of population (two doses) per month
Level 3 (indicative of further scale up)	5% of population (two doses) per month

Vaccination Throughput Level	Value
Level 4 (at full scale, end-2021 going in to 2022)	7% of population (two doses) per month

For context on how these throughput levels compare to existing vaccine rollouts.[3]



*Fraction of population stated reached with two doses. Assumes vaccination activity for 30 days per month. Example: 1% of population per month with two doses is 2% of population per month with one dose. Vaccination for 30 days per month leads to 2/30 = 0.067 doses per 100 people per day.

The system cost elements included are:

- vaccinator team cost (including per diems, personal protective equipment, consumables, and other equipment for the team), excluding salaries,
- vaccination site set up or operating cost (including any equipment, registration, or non-vaccinator staff needed at site),
- transport cost of vaccines and vaccinator teams to the vaccination locations, and
- transport cost of people to reach the vaccination locations.

Transport cost of people to vaccination locations is not a direct cost to for vaccine distribution but is an overall system cost and is needed to reflect the end-to-end cost of getting vaccines into the arms of the population.

[3] While throughput equivalent to 20% of the population monthly is rare, some countries did exceed that level at their peak vaccination rates e.g. Israel, Chile, UAE and more. See some vaccination rates over time here: https://ourworldindata.org/grapher/daily-covid-vaccination-doses-per-capita?country=BHR~BRA~CHL~CHN~DEU~HUN~IND~QAT~RUS~TUR~ARE~GBR~USA~URY~ISR

Element	Value	Sensitivity scenarios explored
Capacity of a vaccinator team	100 doses per day	Allowing part time vaccinator teams. Multiples of 20 people vaccinated (on average) per day. This means we allow vaccinator teams at a location to be active for COVID-19 vaccination for any of 1 through 5 days a week.
Setup/Operating cost of a vaccination site -	$100 per day	$50 per day; $200 per day
Cost per vaccinator team per day	$75 per day	Allowing part time vaccinator teams. $15 cost applied per 20 people vaccinated.
Transport cost of people to vaccination location (from population point to vaccination location) *While not expected to be paid for by the health system, we need to include some cost for people to travel to vaccination sites. to capture system-wide tradeoffs to the health system and vaccine recipients*	$0.25 per km per person	$0.10 per km per person, $0.33 per km per person
Transport cost of vaccine from regional storage locations to vaccination location	$1 per km (for all vaccines transported to a HF in one trip)	

Limitations

The above cost elements do not comprise an exhaustive set of factors to determine concentrated vs dispersed delivery. Below, we list some additional factors not explicitly included by the network optimization model, but should be considered by stakeholders.

Factors that would favor more concentrated delivery:

- Buffer stock: With demand and supply variability, less buffer stock is needed with fewer vaccination locations. A rule of thumb in supply chain is that for the same level of buffer stock, wastage or stock-outs reduce as the square root of the ratio of the number of stocking locations. For example, for the same level of supply and demand variability, 10 vaccination locations would require ~3x less buffer stock than 100 vaccination locations.

- Optimized throughput: Learning and streamlining of processes at high-throughput locations with multiple dedicated vaccinator teams could lead to increased vaccine administration capacity over time, while still using the same number of vaccinator teams.

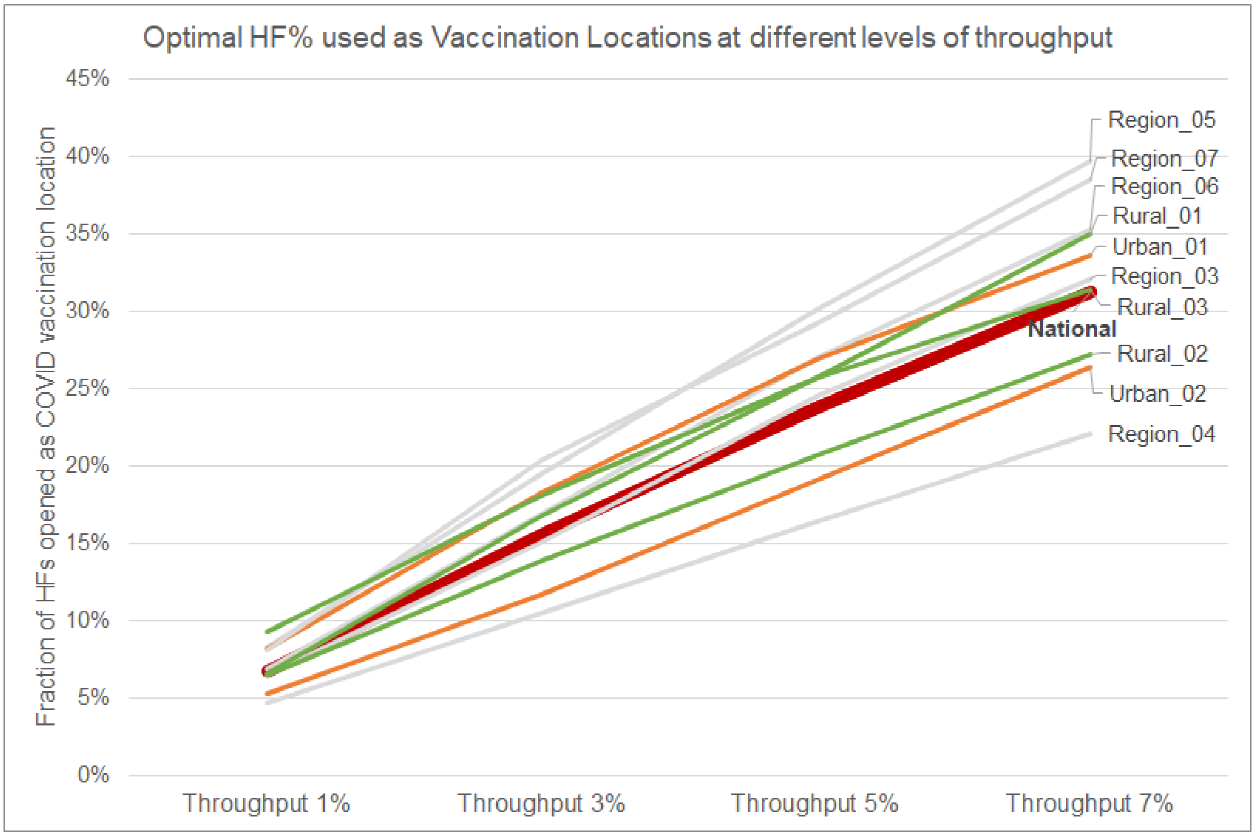
Factors that would favor more dispersed delivery:

- Risk: Dispersed delivery through many smaller sites could potentially reduce risk, because failure at any one individual site would only affect a small number of vaccinations, as any one individual site is small.
- Cold chain capacity: Larger cold chain storage capacity is needed at high throughput locations with concentrated delivery.

Results

1. **HF Usage: All health facilities do not need to serve the COVID-19 vaccine.** The model does not suggest having all health facilities (HFs) serve as vaccination locations when minimizing cost as well as when balancing cost, vulnerability and coverage. At 7% throughput, the model recommends opening 22-40% of HFs as vaccination locations at $2.38 cost/dose. Even with sensitivity analyses, the percentage of HFs opened as COVID-19 vaccination locations never exceeds 65%. When forced to use all existing HFs as vaccination sites at this throughput level, the model shows a 233% increase in cost per dose ($2.38 to $6.58). The cost increase is even higher at lower levels of vaccine throughput.
    a. **Number of HFs used as vaccination locations increases with throughput:** As seen in the graph below, all regions use a higher percent of HF as vaccination locations as vaccine throughput increases. This implies that countries and regions should start with concentrated delivery and then get more dispersed over time as vaccine supply increases.
    b. **Population density and health facility density drive the number of vaccination locations:** Regional characteristics drive the right level of concentration vs dispersion. Population density is the primary driver, followed by health facility density. For regions with high population density and health facility density, the model recommends more concentrated delivery from higher throughput vaccination locations, as people do not have to travel far to be vaccinated. For regions with low population density and health facility density, the model recommends more dispersed delivery from smaller vaccination locations.

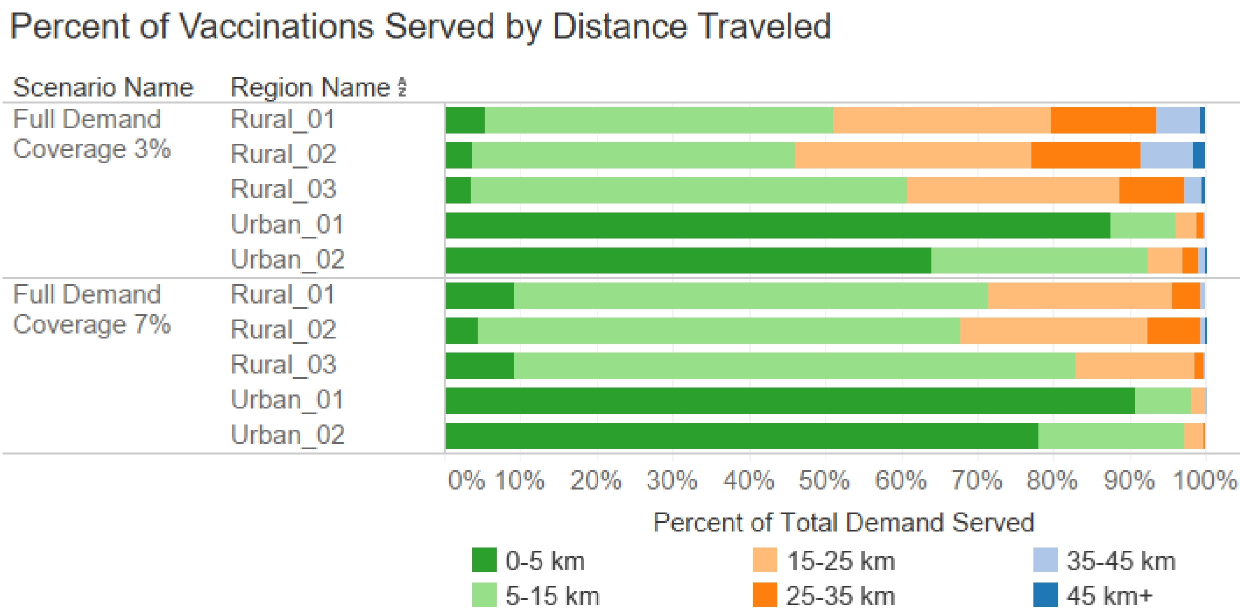
Figure 1. Optimal % of HFs used as vaccination locations at different levels of throughput, with no travel distance constraint for accessing vaccination.



**Rural is < 15 population per km; Urban is > 100 population per km*

2. **Travel distance to vaccination location:** As the vaccination supply increases, the model suggests to open more HFs as vaccination points, lowering the average distance traveled for an individual. However, even in high throughput scenarios, where a larger fraction of HFs are opened as vaccination locations, in the example country ~15+% of the population still has to travel more than 15 km to a vaccination location. The share of people who have to travel long distances is significantly higher in the sparse rural regions, but exists in all regions.

Figure 2. *Percent demand served by region and distance traveled: The results represent 3% and 7% vaccination throughput under standard assumptions. Distance traveled is higher for rural regions and decreases as throughput increases because more HFs are used as vaccination locations. The Urban 01 and Urban 02 regions represent the densest provinces from the sample country with population densities over 100 people per sq km. The Rural 01, Rural 02, and Rural 03 regions represent the three sparsest populated provinces with population density for all under 15 people per sq km. This figure for more scenarios is included in the appendix.*



a. **What if we placed a constraint that all people had to be served by a COVID-19 vaccination location within 15 km?** In this example country, ~15% of the population lives further than 15 km from a HF. To ensure *all populations* are within 15 km of a vaccination location, more vaccination sites beyond existing health facilities would be required. Because of the small populations served by each of these additional vaccination points, these vaccination points could be temporary posts or mobile outreach services. Providing these outreach services to reach the additional 15% of the population would lead to a further increase in system cost that should only be considered with higher level supply. To ensure all populations are within 15 km of an opened vaccination location, the number of vaccination locations and system cost increases significantly for lower throughput (3% throughput, 36% increase in system cost per dose, $4.07 to $5.53) and less significantly for higher throughput (7% throughput, 12% increase in system cost per dose, $2.83 to $3.16).

3. **Mass vaccination locations: Even at high throughputs, few mass vaccination locations are recommended, mainly in urban areas.** These locations together serve a small share of total doses served in the country**:** When vaccinating 7% of the population per month, a few mass vaccination sites (defined by administering at least 1000 doses per day) are recommended as a part of the overall delivery system in large cities. However, mass vaccination sites do not play a significant role in delivery until an even higher vaccination throughput (such as 20% of the population per month, which is the level of throughput of the world's fastest COVID-vaccinating countries are reaching on their peak days) is reached.
    a. For the example country at 7% of population per month throughput, 0-5 mass vaccination locations (i.e. maximum of 5 locations with 10+ vaccinator teams at each) were recommended. Mass vaccination locations were recommended only in the largest city in the country, which has a population over 3 million and

population density 3000 people per sq kilometer. These 5 mass vaccination locations account for 0-6% of daily doses administered in the example country. So even at high throughput, mass vaccination locations play only a niche role.

b. If mass vaccination sites are defined as locations set up to administer >500 doses per day (> 5 vaccinator teams), then the number of mass vaccination locations increases by 2-3x at 7% throughput. For the example country, this represents 8-11 locations and 7-13% share of national doses.

c. The above results hold true even when we allow the model to cluster vaccination locations that the model recommends opening within 4 kms of each other into single vaccination locations. The number of mass vaccination locations remains low as indicated above.

d. If a very high vaccination throughput of 20% of the population per month[4] is considered, then mass vaccination sites (>1,000 doses per day) become a little more important, but are still concentrated in the most urbanized provinces' largest cities. At 20% throughput, 12-20 mass vaccination locations are recommended in the largest city (depending on whether 4km clustering is applied or not). These locations together still only account for ~10% of all daily doses administered in the country. At this throughput level, with 4 km clustering, mass vaccination sites start to emerge in other top ten cities in the country with populations between 100,000 and 500,000 but only 5 additional sites, 4 of which are in the second most urbanized region.

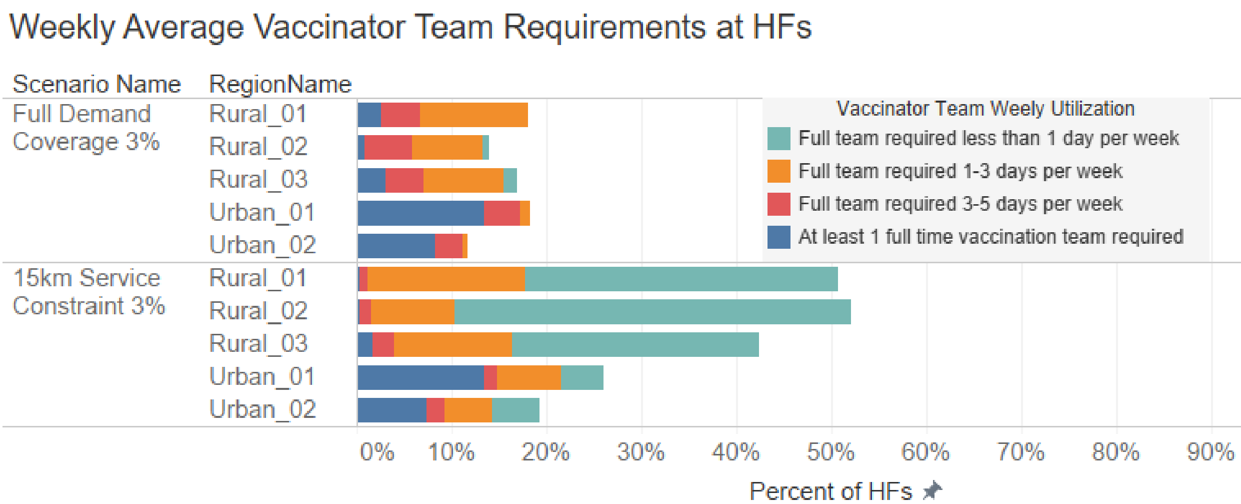
e. If mass vaccination sites are defined as those set up to administer 500 doses per day, then at 20% throughput, these locations become more widespread. 68 of these mass vaccination locations are recommended. 8 of 10 regions have at least 1 mass vaccination site, although about 70% and 15% of them are opened in the top 2 most populated regions, respectively. Collectively, all 68 of these mass vaccination locations account for 20% of all daily doses administered in the country.

4. **Low throughput vaccination locations, which deliver on average less than 60 doses a day (or less than 3 days a week) represent 40-75% of vaccination locations in rural provinces even at high vaccination throughput levels. These small vaccination locations could explore operating for COVID-19 vaccination only part-time, and share human resources and infrastructure with routine vaccination**. On the other hand, in the urban regions (provincial population density greater than 100 people per sq km), even at a lower 3% throughput, the model recommends having at least 85% of opened vaccination sites have at least 1 COVID-dedicated vaccinator team working at least 3 days a week. The amount of full time vaccinator teams required increases significantly with higher throughput as seen in the graph below, even when more HFs are used as vaccination sites.

Figure 3. *Weekly Average Vaccinator Team Requirements at HFs: The graph below shows the percentage of HFs in each region being used as COVID vaccination sites and the average*

[4] Vaccination throughput of 20% of the population per month is rare, but has been observed at peak times in pace-leading vaccinating countries such as UAE, Chile, and Israel.

utilization of vaccinator teams at each site at 3% throughput. The second scenario constrains all demand points to be within 15 km of a vaccination location. Legend can be translated to daily interpretation whereas 1-3 days per week can also be considered as 1.6-4.8 hours per day for vaccination teams that may balance routine vaccination with COVID vaccination. A 5-day week is referenced for simplicity. This figure for more scenarios is included in the appendix.

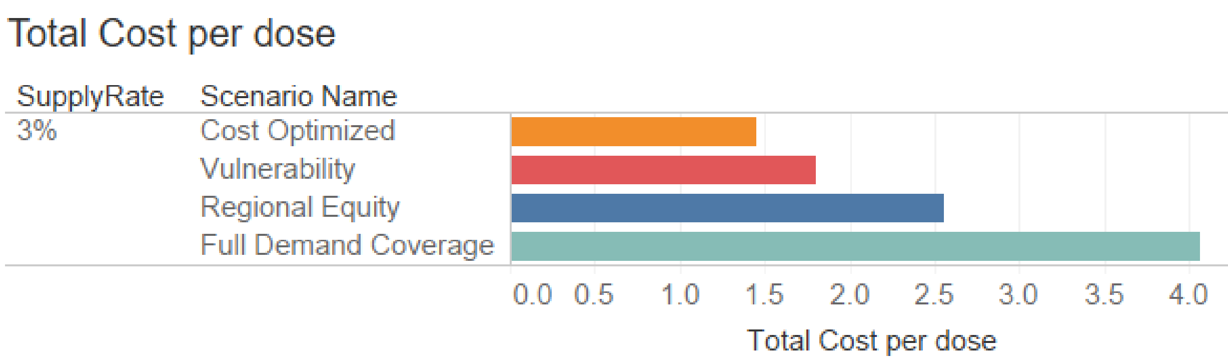


a. **Impact of minimum vaccination site throughput requirement**: Additional sensitivity analysis is explored adding a minimum capacity constraint to ensure full time utilization of vaccination teams if a vaccination site is opened. This constraint reduces the amount of vaccination locations and increases the average distance traveled and system cost per dose, especially in more sparsely populated regions. In the most urbanized region the number of vaccination locations decreases 8-25% and the percent of the population traveling over 15 km increases from 2-7% to 4-10%, depending on throughput. In the regions with the lowest population density, the number of vaccination locations decreases 40-70% and the percent of the population traveling over 15 km increases from 40-70% to 60-85%. This corresponds to a 10-30% increase in system cost in more rural regions where at least 70% of the new cost represents transport cost of people traveling to vaccination sites.

5. **If only minimizing cost, the model recommends allocating most doses to denser urban areas, but when considering vulnerable populations, the model allocates some doses to target more vulnerable areas at a 25% per dose cost increase:**
   a. Using a cost minimizing approach, the model initially chooses to allocate most doses to the denser urban areas of the country (at $1.46 cost per dose for 3% throughput). Those particular urban regions achieve high coverage initially, while other regions only reach small shares of their population. Then as supply increases, the rest of the country starts receiving more doses and achieves higher coverage. At 3% throughput, the model recommends allocating most doses to the two most urbanized regions of the country reaching 90% and 70% coverage; while other rural regions had coverage as low as 10%.

b. However, when vulnerability is introduced into the model using CCVI, the allocation of doses changes. Regions with more vulnerable populations achieve higher coverage earlier. When balancing cost and vulnerability (using CCVI) - at 3% throughput levels, the region with the highest vulnerability index increased coverage from 30% (in the pure cost-minimizing case) to 90% while the coverage in second most urbanized region decreased from 70% (in the pure cost minimizing case) to 50%.The additional system-wide delivery cost when accounting for vulnerability is ~25% higher per dose ($1.46 per dose to $1.80 per dose)

Figure 4. Total system delivery cost per dose for scenarios assuming a vaccine supply to vaccinate 3% of the population per month for cost-driven vaccine allocation, vulnerability driven allocation, vulnerability with regional allocation in proportion to population (shorthand: “regional equity”), and full demand coverage, respectively. See appendix for cost per dose for varying levels of supply and maps for example network views of the alternative allocation strategies.



c. If allocation across regions is enforced evenly as a share of their population, then all regions will achieve the same coverage of their populations. However, this will lead to substantially increased cost by ~40% over free regional allocation accounting for vulnerability ($2.56 per dose compared to $1.80 per dose) and does not even lead to targeting the most vulnerable populations earliest.

Programmatic Recommendations

Broad conclusions for vaccine delivery in LMICs are provided based on the following four categories with the intent to provide general policy guidance.

Vaccination location concentration:

- Not all HFs need to administer COVID-19 vaccines.
- At low levels of vaccine availability (e.g., 1% of the population per month), countries should favor concentrated vaccine delivery using 5-20% of HFs as vaccination locations target largely urban areas in addition to the most vulnerable populations. There is a continuum as supply increases to open more vaccination locations. At higher levels of vaccine availability, (e.g., 7% of the population per month), countries should favor more dispersed vaccine delivery using 20%-45% of HFs as vaccination locations to vaccinate

the majority (~90%) of the country's population. Rural regions should consider using up to 55% of HFs if enforcing service distance levels such as reaching most populations within 15 km of vaccination sites. Additional outreach vaccination locations can be considered for remote populations.

Mass vaccination sites:

- Mass vaccination sites will play a niche role in overall delivery, even at higher feasible levels of vaccination throughput.
- To vaccinate 7% of the population per month, countries can open 0-5 mass vaccination sites (administering >1,000 doses per day) in urban areas with over 3 million people and 3000 people/sq km. These sites would require a dedicated full-time health workforce. Vaccination sites operating at this level are not required for rural areas or in cities with less than 500,000 population.
- If vaccine supply to vaccinate 20% of the population per month is available (which is equal to the very highest current national vaccination rates), countries can plan for some more mass vaccination locations, but these would still deliver a minority of total doses being delivered in the country. At these very high throughput levels, in the most urbanized districts (with 3 million people and 3,000 people/sq km population density), 10-30% of vaccination sites can be mass vaccination locations.

Health workforce:

- In regions with population density of 100+ people per sq km, at least one full-time COVID-19 vaccinator team is needed at 70% of vaccination sites. In these regions, these sites with dedicated vaccinator team requirements serve 85%-95% of the population being covered. The most urban districts in these regions should plan for dedicated full time teams even at low vaccination throughput levels.
- In sparsely populated or rural areas, part time COVID-19 vaccinator teams can play a larger role. In rural regions, at low vaccination throughputs (3% of the population monthly), 50-70% of COVID-19 vaccination sites will require a team working 1-3 days a week on COVID-19 vaccination. Even at higher throughput levels (7% of the population monthly), 30-50% of vaccination sites in rural regions would need 1 team working 1-3 days/week on COVID-19 immunization. This is time that health workers would need to reallocate from routine health services to COVID-19 immunization.

Balancing targeting vulnerable populations, reducing access distance, and cost-efficiency in vaccine delivery

- Vulnerable populations should be prioritized for immunization based on SAGE guidelines. In our example country, targeting the most vulnerable populations leads to a delivery cost of $1.80/dose at vaccination throughput levels of 3% of the population per month. At the same throughput level, focusing only on efficiency would reduce delivery costs by 20% to $1.46/dose, but would lead to immunization centered largely in urban areas and only partially address the people who most need COVID-19 vaccination. Distributing vaccines by region in proportion to population is not recommended, as it is not only more costly at $2.56/dose but also does not specifically target the most vulnerable populations.

- Countries should define the reasonable acceptable distance for people to travel to get vaccinated based on country context. To ensure access to vaccines is available within 15km for people, mobile/outreach is necessary. This increases the vaccine delivery cost that should be included in the budgeting for vaccine deployment. In the example country, the increase in delivery cost per dose ranged from 12% at high throughput (7% of population monthly) to 36% at lower throughput (3% of the population monthly) to bring all people to be vaccinated within 15 km of a vaccination location.
- While these cost estimates are not applicable across all countries, they are directionally indicative of vaccine delivery approaches.

APPENDIX

Scenario Summary: The following table shows a summary of select scenarios run for this study based on varying levels of vaccine supply (as indicated by supply rate). Coverage indicates if a scenario enforces vaccine delivery to all populations (full) or allows for partial or delivery. Details of the following Scenario Descriptions are below where the same scenario set up was carried out for each supply level.

- **Standard Assumptions (Full Demand Coverage)**: This includes assumptions as reflected in the *Input Assumptions* section and enforces full population coverage of all demand points. Standard assumptions apply to all following scenarios where no exceptions are explicitly stated.
- **15 km Service Constraint:** This includes service constraints enforcing all demand points (HFs) to be within 15 km of a vaccination location. The *Avg Travel Distance* and *% Served > 15 km* columns below reflect adjusted distances where average population distances to HFs are considered. This represents a more accurate travel distance for the population and is why a small percent of populations still travel more than 15 km to a vaccination location in the service constraint scenario.
- **High Travel Cost**: This assumes a 33% higher transportation cost for travel to vaccination locations for sensitivity analysis.
- **Low Team & Setup Cost**: This assumes a lower team cost and vaccination site set up cost cost for sensitivity analysis
- **Cost Optimized:** The model chooses where to send the available vaccine supply, not enforcing equal allocation of vaccine supply among regions nor considering vulnerable populations. The results are driven solely by lowest cost.
- **Vulnerability**: The model chooses where to send the available vaccine supply, not enforcing equal allocation of the supply among regions, but providing higher coverage to more vulnerable regions. The results are driven by a balance of lowest cost and serving the most vulnerable populations.
- **Population-based Equal Allocation by Region (referred to as "Regional Equity" for shorthand)**: The model forces proportionally equal regional allocation of vaccines but chooses where to send each region's supply based on lowest cost and vulnerability assigned at the district level.

Scenario Summary

Supply Rate	Coverage	Scenario Description	Total Cost per dose	Avg HF%	Avg Travel Distance	Population Coverage	% Served > 15 km
1%	Full	Standard Assumptions	6.2	7%	15.7	100%	42%
		15 km Service Constraint	13.4	33%	7.8	100%	4%
		High Travel Cost	7.3	8%	14.3	100%	39%
		Low Team & Setup Cost	4.6	15%	10.5	100%	25%
	Partial	Cost Optimized	1.6	3%	1.9	14%	0%
		Vulnerability	2.3	4%	5.5	14%	1%
		Regional Equity	2.3	4%	5.9	14%	3%
3%	Full	Standard Assumptions	4.1	16%	10.1	100%	23%
		15km Service Constraint	5.4	34%	7.3	100%	4%
		High Travel Cost	4.7	19%	9.2	100%	19%
		Low Team & Setup Cost	3.0	34%	6.9	100%	7%
	Partial	Cost Optimized	1.5	6%	3.3	43%	0%
		Vulnerability	1.8	8%	4.3	43%	2%
		Regional Equity	2.6	12%	6.6	43%	7%
5%	Full	Standard Assumptions	3.3	24%	8.2	100%	15%
		15km Service Constraint	3.8	37%	6.8	100%	3%
		High Travel Cost	3.7	28%	7.6	100%	11%
		Low Team & Setup Cost	2.4	46%	6.0	100%	3%
	Partial	Cost Optimized	2.0	16%	5.1	71%	1%
		Vulnerability	2.3	18%	5.8	71%	5%
		Regional Equity	2.5	20%	6.6	71%	7%
7%	Full	Standard Assumptions	2.8	31%	7.2	100%	10%
		15km Service Constraint	3.1	41%	6.5	100%	3%
		High Travel Cost	3.1	35%	6.8	100%	7%
		Low Team & Setup Cost	2.1	55%	5.7	100%	2%
	Partial	Cost Optimized	2.8	31%	7.2	100%	10%
		Vulnerability	2.8	31%	7.3	100%	10%
		Regional Equity	2.8	31%	7.3	100%	10%
20%	Full	Standard Assumptions	1.7	59%	5.5	100%	2%

Scenario Summary by Province Type: The following table shows the results of the scenarios explained above with supply to vaccinate 3% of the population per month for different province types in the example country. Provinces were categorized into the following groups based on the following:

- **Urban**: provinces with highest population density (over 100 people sq km)
- **Rural**: provinces with lowest population density (under 15 people per sq km)
- **Vulnerable**: provinces with highest CCVIs (over 0.6)
- **Non-Vulnerable**: provinces with lowest CCVIs (under 0.25; these provinces were neither classified as rural or urban)
- **Other**: all other provinces that were not classified into the above categories

Scenario Summary by Province Type

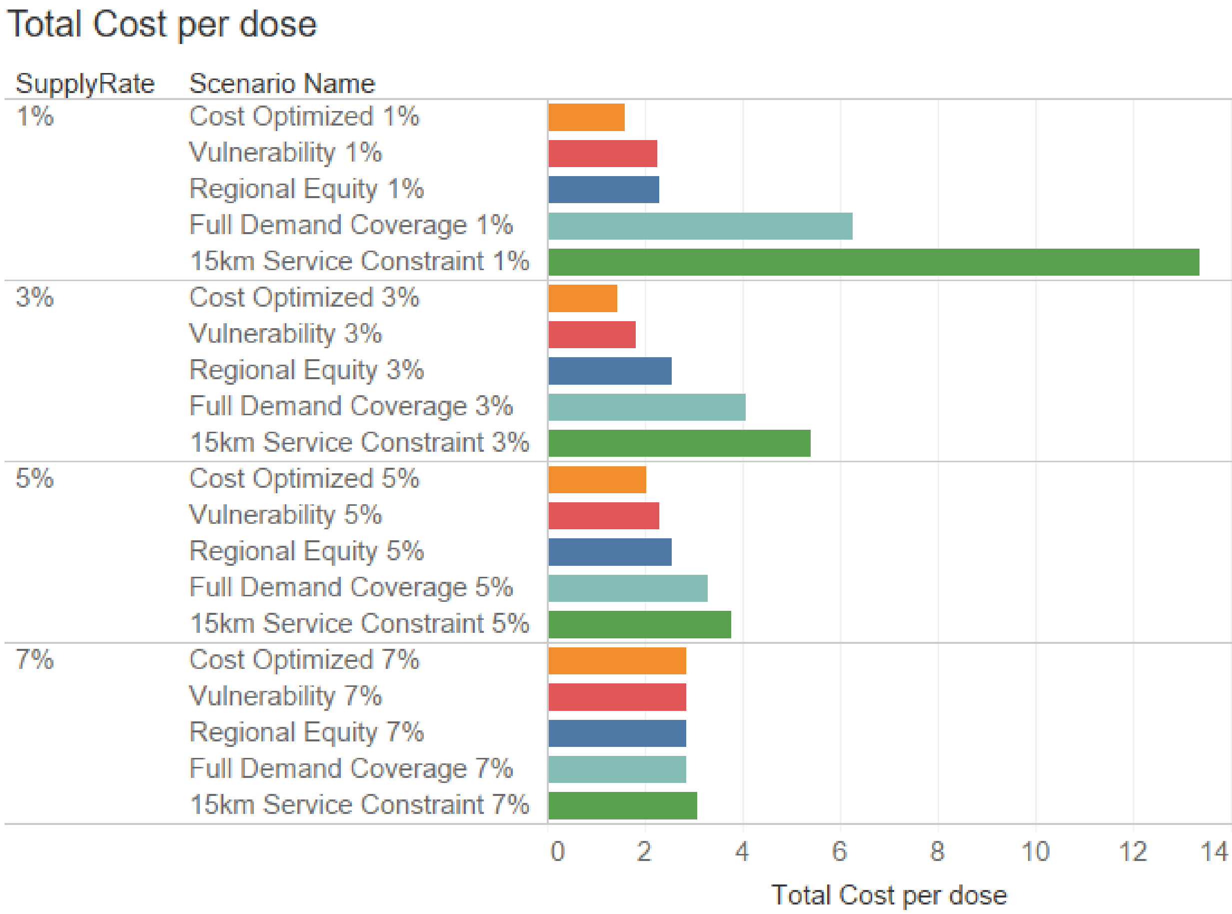
Supply Rate	Coverage	Scenario Description	Province Type	Total Cost per dose	Avg HF%	Avg Travel Distance	Population Coverage	% Served > 15 km
3%	Full	Standard Assumptions	Urban	2.2	14%	4.5	100%	6%
			Rural	6.0	17%	15.6	100%	44%
			Rural-Vulnerable	6.8	14%	18.1	100%	54%
			Vulnerable	4.2	17%	10.6	100%	20%
			Non-Vulnerable	4.7	14%	12.5	100%	32%
			Other	4.5	17%	11.4	100%	25%
			Total	4.1	16%	10.1	100%	23%
		15km Service Constraint	Urban	2.5	22%	3.8	100%	1%
			Rural	8.8	47%	10.0	100%	11%
			Rural-Vulnerable	12.5	52%	10.1	100%	8%
			Vulnerable	5.1	30%	8.2	100%	2%
			Non-Vulnerable	6.2	32%	8.7	100%	3%
			Other	5.5	32%	8.8	100%	4%
			Total	5.4	34%	7.3	100%	4%
	Partial	Cost Optimized	Urban	1.3	17%	2.0	83%	0%
			Rural	1.8	2%	6.1	16%	0%
			Rural-Vulnerable	1.8	1%	6.1	11%	0%
			Vulnerable	1.8	8%	5.4	30%	0%
			Non-Vulnerable	1.7	4%	5.3	27%	0%
			Other	1.7	4%	5.6	23%	0%
			Total	1.5	6%	3.3	43%	0%
		Vulnerability	Urban	1.2	12%	1.8	71%	0%
			Rural	2.2	6%	7.2	29%	3%
			Rural-Vulnerable	3.6	14%	10.8	65%	21%
			Vulnerable	2.5	28%	6.5	88%	1%
			Non-Vulnerable	0.0	0%	0.0	0%	0%
			Other	1.6	4%	5.8	19%	0%
			Total	1.8	8%	4.3	43%	2%
		Regional Equity	Urban	1.3	9%	2.3	43%	1%
			Rural	3.7	14%	10.3	43%	17%
			Rural-Vulnerable	4.2	12%	12.7	43%	29%
			Vulnerable	3.1	16%	8.1	43%	5%
			Non-Vulnerable	2.8	11%	7.7	43%	7%
			Other	2.9	14%	8.0	43%	8%
			Total	2.6	12%	6.6	43%	7%

HF Percent Range: The range of percent HF usage as vaccination locations varies based on vaccine throughput. The number of vaccination sites (HF%) increases as vaccination throughput, or available supply increases. Below are the ranges for each throughput level observed across all regions for standard assumptions and all sensitivity scenarios explored. For scenarios not enforcing distribution of vaccines between regions in proportion to their population, the HF% can drop below the lower bound for neglected regions.

Throughput Level	Standard Assumptions	Including All Sensitivity Scenarios
Level 1 (1% per month)	5% - 9%	3% - 20%
Level 2 (3% per month)	11% - 20%	6% - 45%
Level 3 (5% per month)	16% - 30%	10% - 56%
Level 4 (7% per month)	22% - 40%	13% - 65%

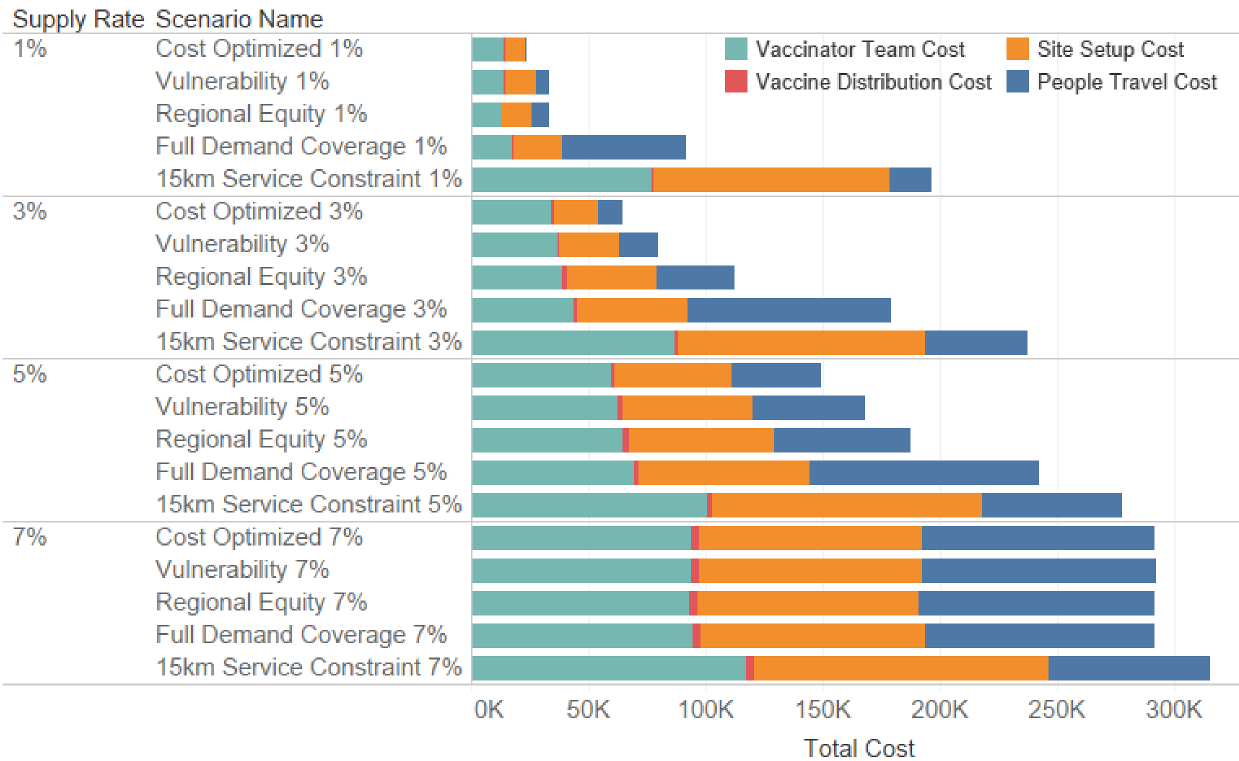
Total System Delivery Cost per dose: The graph below shows total system delivery cost per dose for each of the following scenarios. Each set of 4 scenarios was replicated under varying throughput or supply availability rates (vaccinating 1-7% of the population per month). With the assumption that all vaccine supply will be used, supply and throughput are assumed to be equal in this study. Within each set, see scenario descriptions below.

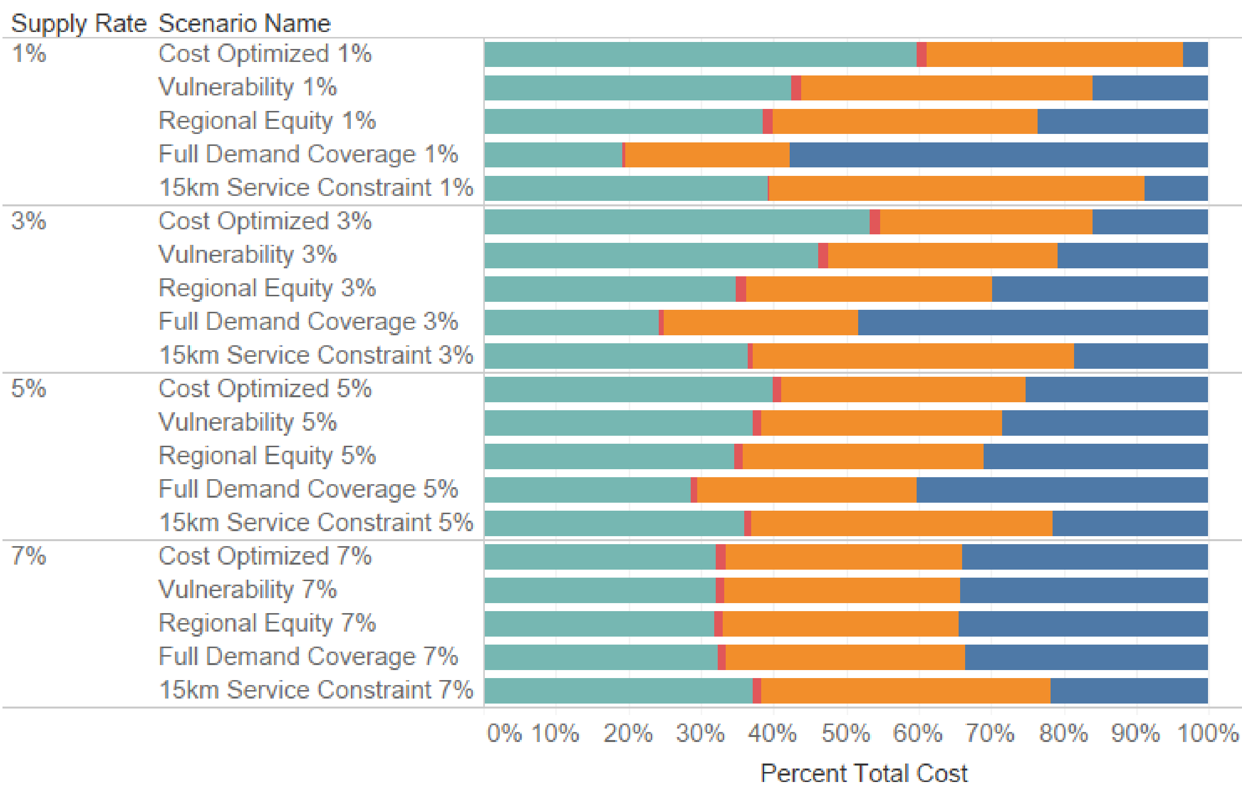
- *Cost Optimized X%* - The model chooses where to send X% of available vaccine supply, not enforcing equal allocation of vaccine supply among regions nor considering vulnerable populations. The results are driven solely by lowest cost. X refers to the supply available to vaccinate X% of the population monthly. See the appendix section *System delivery cost by cost component* for further scenario cost breakdown.
- *Vulnerability X%* - The model chooses where to send X% of available vaccine supply, not enforcing equal allocation of the supply among regions, but providing higher coverage to more vulnerable regions. The results are driven by a balance of lowest cost and serving the most vulnerable populations.
- *Regional Equity X%* - The model forces proportionally equal regional allocation of vaccines but chooses where to send X% of each region's supply based on lowest cost and vulnerability assigned at the district level.
- *Full Demand Coverage X% (Standard Assumptions)* - All demand points throughout the example country must be served portionally equal based on their respective population. Standard assumptions apply. This and the next scenario require all demand points to be served, thus, reflecting the higher total system cost.
- 15 km Service Constraint X% - All demand points throughout the example country must be served portionally equal based on their respective population within 15 km of a vaccination location. This constraint at low vaccine throughput levels, significantly increases system cost per dose.
- *Note*: For the 7% supply availability scenarios, all demand points are served in each scenario, thus, showing no differences in total cost per dose for the first four scenarios.



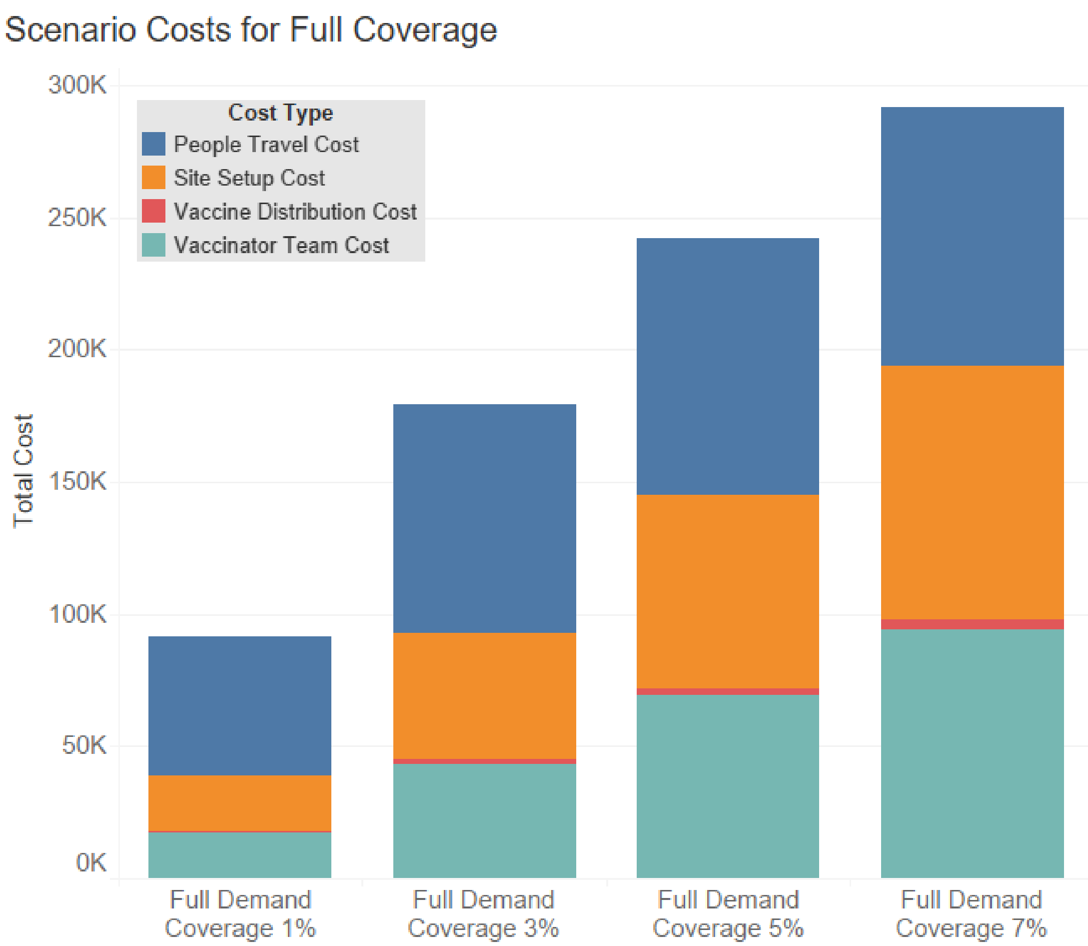
System Delivery Cost by Cost component: The graph below shows model scenario costs for varying supply availability broken down into the four cost components the model considers: vaccinator team cost, vaccine distribution cost, vaccination site set up cost, and people travel cost to vaccination sites. All scenarios below following the standard cost assumptions as outlined in the *Input Assumption Values* section. Scenario descriptions of the following scenarios are included in the *Total System Delivery Cost per dose* Appendix section. In the *Full Demand Coverage 3%* scenario, people travel cost makes up about 50% of the total system cost as all demand points are served. The total cost drops significantly in all cost components when equal vaccine allocation for all demand points is not required, most notably for individual travel cost. The costs increase as vulnerability and fixed regional allocation are introduced to the model.

Cost per Dose by Cost Component

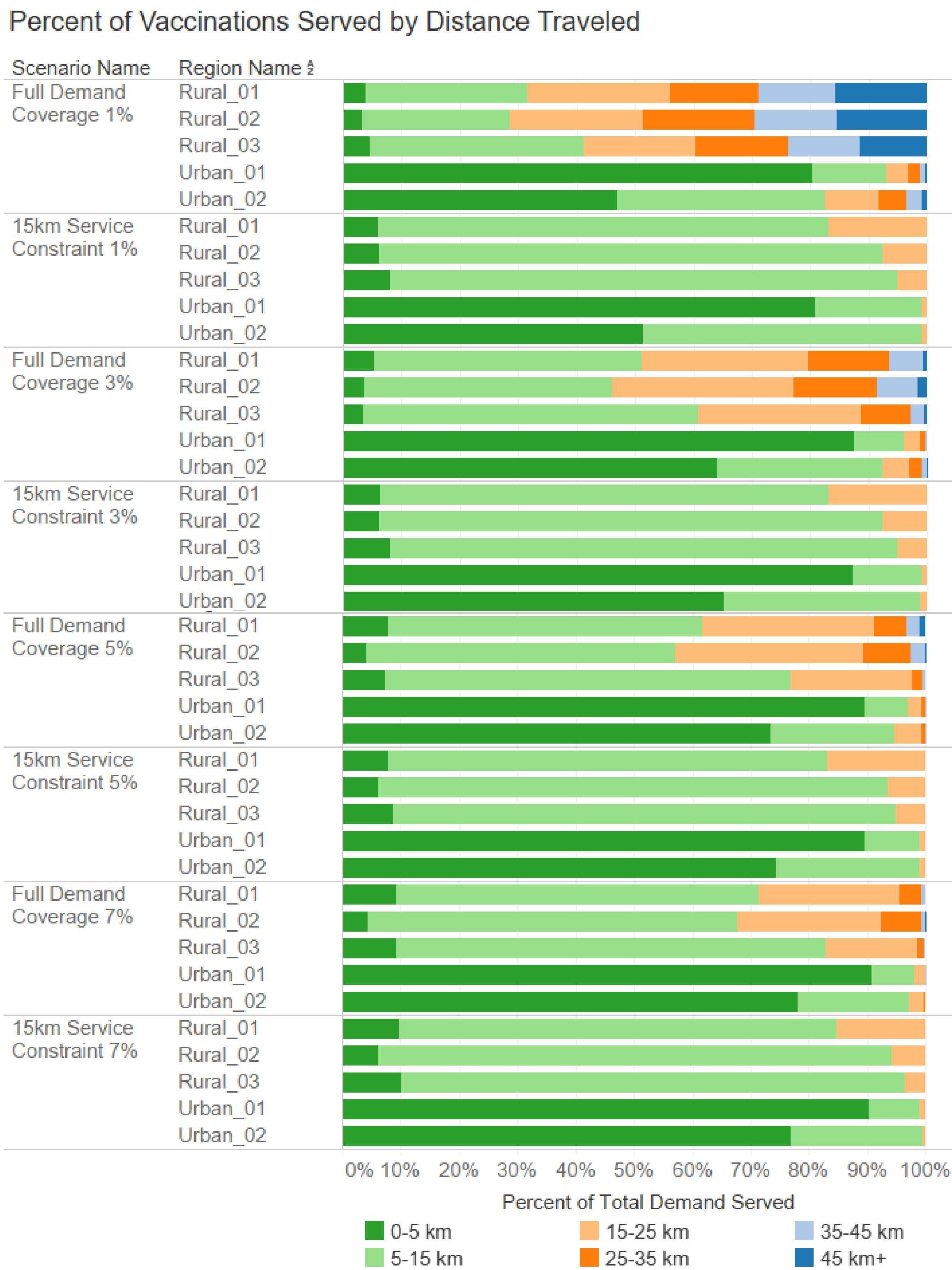




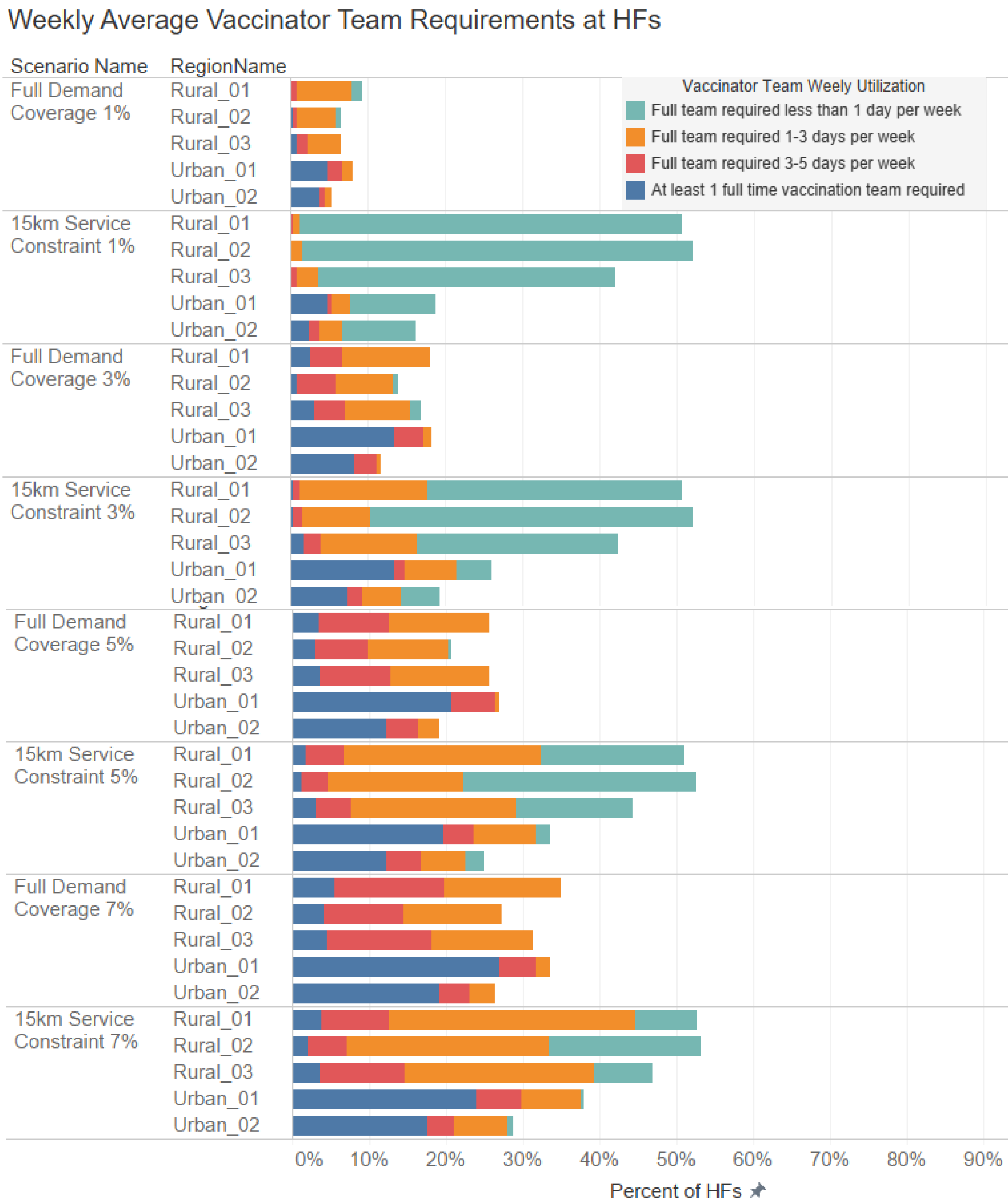
Scenario Costs for Full Coverage: The figure below shows total costs for Full Demand Coverage (standard assumption) scenarios by throughput level. The total costs should not be used directly in budget allocation, but are directionally indicative of total cost increases as vaccine supply availability and throughput increase.



Distance Traveled by Scenario: This shows the figure in *Results* section 2 extended for full coverage scenarios at varying throughputs and a distance constraint addition.



Weekly Average Vaccinator Team Requirements at HFs: This shows the figure from *Results* section 4 extended for full coverage scenarios.

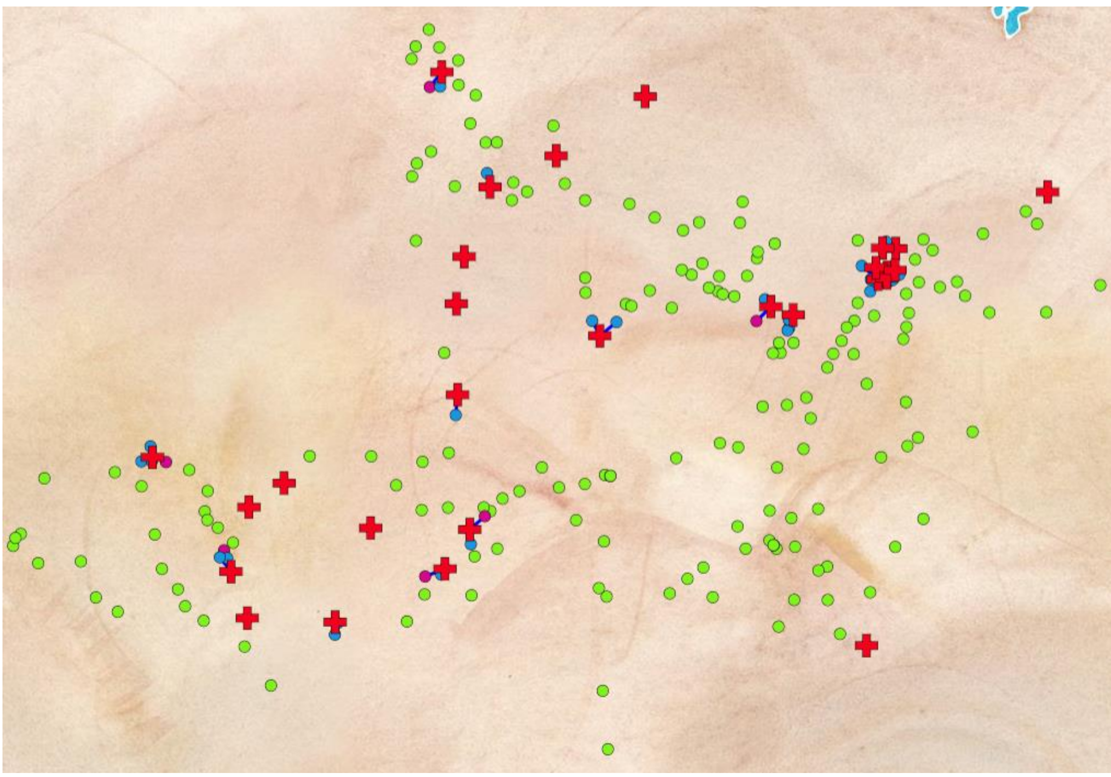


Examples of Vaccination Allocation Differences: Below shows examples of coverage and allocation strategies in order of lowest to highest system cost per dose: allocation with only cost considered, allocation with vulnerability considered, full demand point coverage, and full demand point coverage with distance constraint forcing all demand to be within 15 km of a vaccination location.

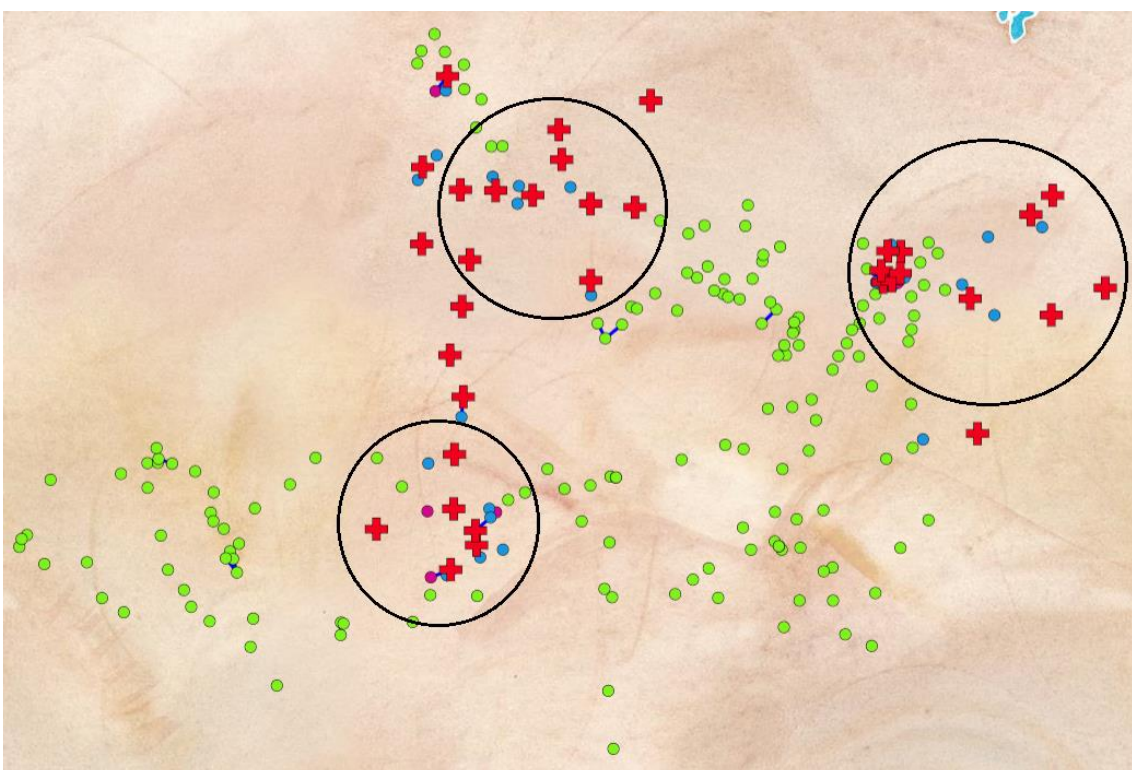
Legend:

Symbol	Description
	Not served demand center (HF)
	Partially served demand center (HF)
	Fully served demand center (HF) (i.e., based on 7% of population per month target)
	HF opened as a vaccination site (marker covers demand locations for collocated sites
(blue line)	People travel to vaccination site
(circle)	Vulnerable Region

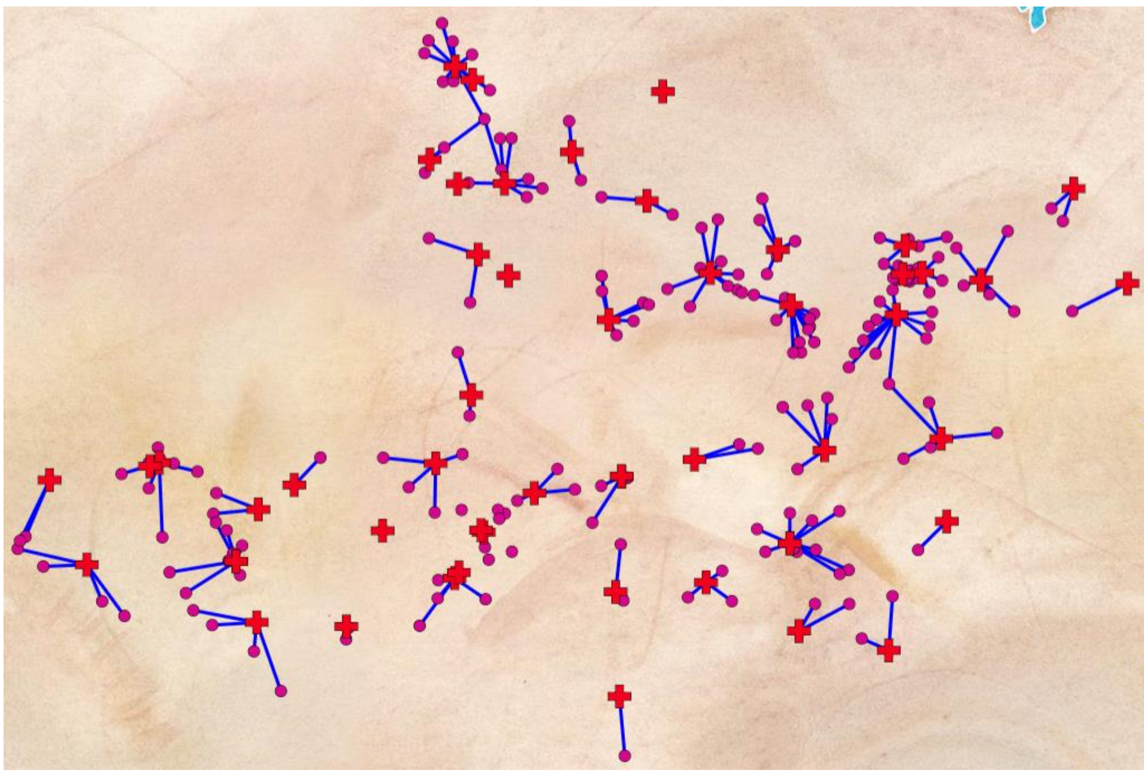
1. *Cost-efficient vaccine allocation, no vulnerability considered, select demand to satisfy:*



2. *Vaccine allocation w/ vulnerability considered (CCVI),select demand points to satisfy:*



3. Vaccine allocation, equal coverage of all demand points:



4. Vaccine allocation, equal coverage of all demand points, with 15 km service constraint: