Optimising scale and deployment of community health workers in Sierra Leone: a geospatial analysis

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ABSTRACT

Background Little is known about strategies for optimising the scale and deployment of community health workers (CHWs) to maximise geographic accessibility of primary healthcare services.

Methods We used data from a national georeferenced census of CHWs and other spatial datasets in Sierra Leone to undertake a geospatial analysis exploring optimisation of the scale and deployment of CHWs, with the aim of informing implementation of current CHW policy and future plans of the Ministry of Health and Sanitation.

Results The per cent of the population within 30 min walking to the nearest CHW with preservice training increased from 16.1% to 80.4% between 2000 and 2015. Contrary to current national policy, most of this increase occurred in areas within 3 km of a health facility where nearly two-thirds (64.5%) of CHWs were deployed. Ministry of Health and Sanitation-defined ‘easy-to-reach’ and ‘hard-to-reach’ areas, geographic areas that should be targeted for CHW deployment, were less well covered, with 19.2% and 34.6% of the population in 2015 beyond a 30 min walk to a CHW, respectively. Optimised CHW networks in these areas were more efficiently deployed than existing networks by 22.4%–71.9%, depending on targeting metric.

Interpretations Our analysis supports the Ministry of Health and Sanitation plan to rightsize and retarget the CHW workforce. Other countries in sub-Saharan Africa interested in optimising the scale and deployment of their CHW workforce in the context of broader human resources for health and health sector planning may look to Sierra Leone as an exemplar model from which to learn.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Previous studies in Sierra Leone have explored geographical accessibility to antenatal care and childbirth services at health facilities but not community-based primary healthcare (PHC) services provided by community health workers (CHWs).

WHAT THIS STUDY ADDS

⇒ Our analysis provides new insight on the contribution of CHWs to increasing geographical accessibility of community-based PHC services in Sierra Leone between 2000 and 2015, as well as policy relevant variation across subnational areas, gender of the CHW and training of the CHW on specific interventions.
⇒ Our analysis identifies important misalignment between the scale and geographic distribution of the existing CHW workforce and current national policy, and points to opportunities for optimising scale and efficiency of CHW deployment.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE AND/OR POLICY

⇒ Our analysis supports Ministry of Health and Sanitation (MOHS) plans to rightsize and retarget the CHW workforce.
⇒ The MOHS could use our analysis and future iterations to fine-tune planning and implementation of CHW policy in the context of broader HRH and health sector planning.
⇒ MOHS and partners could consider re-investing cost-savings from rightsizing and retargeting towards the professionalisation of CHWs and strengthening the systems components needed to optimise CHW performance.

BACKGROUND

Countries committed to achieving Universal Health Coverage (UHC) as part of the Sustainable Development Goals set in 2015 and reaffirmed that commitment at the United Nations General Assembly High Level Meeting on UHC in 2019. Achieving UHC and ensuring effective pandemic preparedness and response will require strengthening health systems by investing in primary healthcare (PHC), particularly frontline health workers at the primary healthcare level and in communities. CHWs are foundational to the PHC approach as frontline human resources for health (HRH), essential members of PHC teams providing community-based PHC services and a trusted
bridge between the health system and communities.\textsuperscript{6-9} Research has shown CHWs can be a cost-effective and equity-promoting investment, particularly when they are well-supported by the health system and communities they serve.\textsuperscript{10-15} Investment in CHWs can also promote the economic development and the empowerment of women through paid work.\textsuperscript{10,16} Globally, there is a severe HRH shortage, including for CHWs, compounded by a maldistribution of HRH, with the most severe affects in Africa, particularly in rural, remote and underserved geographic areas.\textsuperscript{17,18} Globally, financing of HRH is inadequate, including for CHWs with an estimated funding gap of US$5.4 billion annually.\textsuperscript{19}

In Sierra Leone, CHWs are essential frontline HRH critical to the country’s vision of a resilient national health system and prosperous socioeconomic development.\textsuperscript{20-22} Under the leadership of the Ministry of Health and Sanitation (MOHS), there was a large scale-up of CHWs employed by non-governmental organisations between 2000 and 2020, including during the Ebola crisis.\textsuperscript{25} As of 2020, there were >17,000 CHWs deployed in Sierra Leone.\textsuperscript{25} An assessment of the national CHW programme incorporated findings from earlier iterations of our analysis, and informed the new MOHS CHW policy for the period 2021–2025.\textsuperscript{23} The new policy included three key policy shifts: harmonisation and integration of all CHW cadres into the national CHW programme, rightsizing the scale of the CHW network and retargeting CHW deployment to areas of greatest need.\textsuperscript{24}

Policies strive to increase financing for HRH, including for CHWs, concurrent efforts are needed to optimise impact and efficiency of available funding through rightsizing scale and improving the equitable distribution of HRH, including CHWs. Geospatial analysis using geographic information systems can be a powerful tool in the HRH toolkit for optimising scale and deployment of HRH. However, few countries leverage the potential of geospatial analysis, contributing to inefficiencies and inequities in the distribution of HRH and geographical accessibility of health services.\textsuperscript{17,18}

We used data from a national georeferenced census of CHWs and other spatial datasets in Sierra Leone to undertake a geospatial analysis exploring optimisation of the scale and deployment of CHWs with the aim of informing implementation of the new CHW policy and future MOHS planning.

**DATA AND METHODS**

We provide a detailed description of the data and methods in online supplemental appendix 1, including a simplified analysis flow (online supplemental appendix 1 figure 1). Methods were adapted from previous work in the region by Oliphant et al.\textsuperscript{25}

**Study setting**

During our period of focus, 2000–2016, Sierra Leone had four political administrative levels (chieftdoms, districts, provinces and national).\textsuperscript{26} The health system included a public and private sector organised in a decentralised, pyramidal structure with three administrative levels—tertiary, secondary and primary—overseen by the MOHS.\textsuperscript{27} Our analysis focuses on CHWs situated at the base of the primary level. The primary level comprised public health facilities, collectively known as peripheral health units (PHUs) providing PHC and referral services to the secondary level (district hospitals). PHUs—in descending order according to size and availability of skilled healthcare workers—include community health centres, community health posts and maternal and child health posts. The primary level also included private sector clinics focused on primary healthcare services.

At the base of the primary level were CHWs. National CHW policy evolved over time, including the development of the first national CHW policy in 2012 (covering 2012–2015),\textsuperscript{18} and subsequent updates in 2016 (covering 2016–2020)\textsuperscript{21} and 2021 (covering 2021–2025).\textsuperscript{23} According to the national CHW policy of 2012–2015, a CHW was defined as a community member selected by the community and trained to provide basic essential health services and information at community level.\textsuperscript{28} Following a standardised 10-day preservice training designed by the MOHS, CHWs were allowed to provide a standard package of community-based PHC services, including prevention, promotion and curative services, as well as surveillance activities, through household visits. The national CHW policy of 2012–2015 did not include geographic criteria for guiding the deployment of CHWs (ie, the CHW could be selected from and work in communities regardless of proximity to health facilities). The national CHW policy of 2021–2025 sought to rightsize and retarget the CHW network and was informed, in part, by early iterations of our analysis.\textsuperscript{23,24} Additional details on the evolution of CHW policy, including the definition of CHWs, package of services, selection, training, certification, deployment, CHW per population ratios and supervision are provided in online supplemental appendix 1.

**Data**

We obtained the following spatial datasets to inform our models of travel time to CHWs and health facilities: administrative boundaries (levels 0–3),\textsuperscript{29} a 2016 national georeferenced master facility list (Ministry of Health and Sanitation, the Republic of Sierra Leone, UNICEF, 2016), a 2016 national georeferenced CHW master list (CHWML) (Ministry of Health and Sanitation, the Republic of Sierra Leone, UNICEF, 2016), digital elevation model,\textsuperscript{30} land cover,\textsuperscript{31} roads,\textsuperscript{32} waterbodies\textsuperscript{33} (treated as barriers to movement where roads did not cross) and travel scenarios (online supplemental appendix 1 figures 27–37). As of 2016, there were 14,632 working CHWs of which 14,579 CHWs (99.6%) had geographic coordinates for the main settlement in which they worked and 14,494 CHWs (99.1%) reported they received the standard 10-day preservice training of the MOHS (online supplemental appendix 1 figure 38). Data on training
and year of deployment were self-reported by CHWs in the CHWML. For our analysis of accessibility coverage, geographic coverage and efficiency of deployment, we obtained modelled estimates for population counts for 2000–2015. 34 35 Community-based PHC services provided by CHWs are intended to address under-five (U5) mortality and malaria was a main cause for curative consultations among children U5 in Sierra Leone. 27 For this reason, we obtained modelled estimates of the annual mean U5 mortality rate in 2015 36 and modelled estimates of the annual mean incidence of Plasmodium falciparum (Pf) malaria among all ages (0–99 years) in 2015 37 to inform our efficiency analysis. We prepared the input datasets in the projected coordinate reference system EPSG:2161—Sierra Leone 1968/UTM zone 28N for Sierra Leone at 100 m×100 m resolution for our analysis of accessibility coverage and 1 km×1 km for our analysis of geographic coverage and efficiency of deployment.

We prepared a travel speed table for the travel scenario walking in dry conditions (online supplemental appendix 1). We adapted travel speeds for each land cover class and road class from previous studies. 25 38 39 Travel speeds refer to the population walking in dry conditions in the direction of the CHW. Travel speeds and analysis for other travel scenarios (eg, travel in wet conditions, motorised travel) that were not our main focus are provided in online supplemental appendix 1.

Geographic areas relevant to CHW policy

The current CHW policy for 2021–2025 included two policy-relevant geographic areas: easy-to-reach (ETR) and hard-to-reach (HTR) areas. 24 The MOHS defined ETR areas as areas 3–5 km from a health facility and not in difficult terrain. The MOHS did not define ‘not in difficult terrain’. Hills, mountains and water bodies can increase the travel time needed to traverse an area or impede travel altogether, depending on the mode of transport. We accounted for the effect of such geographic features on travel time in our analysis and defined ‘not in difficult terrain’ as areas within 60 min walking of a health facility. The MOHS-defined HTR areas as areas beyond 5 km from a health facility or between 3 and 5 km of a health facility and in an area with difficult terrain. The MOHS did not define ‘difficult terrain’. We defined ‘difficult terrain’ as beyond 60 min walking of a health facility. This is a change from previous definitions of ETR and HTR areas in Sierra Leone. In the CHW policy for 2016–2020, the MOHS defined ETR as areas within 3 km of a health facility and HTR areas as areas beyond 3 km from a health facility. 21 The MOHS definitions of ETR and HTR areas in the 2016–2020 policy did not mention ‘difficult terrain’. The CHW policy of 2012, covering the period 2012–2015, did not provide definitions for HTR and did not mention ETR. 28

We conducted our analysis for three geographic areas relevant to the current CHW policy for 2021–2025: areas within 3 km of a health facility, which are not prioritised for CHW deployment in the 2021–2025 CHW policy, ETR areas and HTR areas. Populated areas within 3 km of a health facility covered a total of 12 990 km² with an estimated population of 5.5 million in 2015 (77.2% of the total population). Populated ETR areas covered a total of 3 345 km² with an estimated population of 167 000 in 2015 (2.4% of the total population). Populated HTR areas covered a total of 14 878 km² with an estimated population of 1.4 million in 2015 (20.2% of the total population). Further details on the data and methods used to derive these geographic areas are in online supplemental appendix 1.1.

Assessing accessibility coverage

We defined accessibility coverage as the estimated percentage of people within a given travel time to the nearest health service delivery location, accounting for travel speeds of different modes of transportation over different land cover classes. 39 The slope of the terrain is accounted for by correcting for walking speeds, 40 and by considering a direction of travel towards the health service delivery location. 30

We estimated accessibility coverage at 100 m×100 m resolution for the health facility and CHW networks in 2015. We also did this for the CHW networks in ETR and HTR areas, gender of the CHW, year of deployment (2000–2015), preservice training and training on specific interventions. We used 10 min, 30 min and 60 min cut-offs as previous analyses have shown care seeking decays as a function of travel time after these cutoffs 41 and they are clinically relevant (eg, for prompt treatment of severe illness). 42 The analysis was constrained to national borders but allowed for travel across subnational administrative boundaries. We used the ‘accessibility’ module within AccessMod 5 (V.5.6.56) 41 to calculate travel time layers and the ‘zonal statistics’ module to calculate zonal statistics for each travel time layer by administrative level.

Assessing efficiency of deployment in ETR and HTR areas

We assessed the efficiency of deployment of the existing CHW networks and compared them with hypothetical networks designed to optimise efficiency of CHW deployment. We defined efficiency of deployment as the geographic coverage of the estimated population achieved by a given number of CHWs, based on an adaptation of the definition of technical efficiency by Palmer and Torgerson. 43 A CHW network designed to optimise efficiency of CHW deployment is one that maximises geographic coverage of the population with the fewest number of CHWs. This requires deploying CHWs such that each CHW maximises the gain in geographic coverage of the population. We assessed efficiency of deployment by comparing the gain/loss in geographic coverage achieved by optimised CHW networks compared with the existing CHW networks, given the same number of CHWs. We defined geographic coverage as the estimated population within a theoretical catchment area of the CHW networks, given a 30 min maximum travel time (walking scenario) and the maximum population capacity of the

We assessed geographic coverage of (a) the estimated population in 2015, (b) the estimated U5 deaths in 2015 and (c) the estimated *Pf* malaria cases in 2015 by the existing CHW networks in 2016 at 1 km×1 km resolution using the ‘geographic coverage’ module of AccessMod 5 (V.5.6.56).39 We then assessed geographic coverage of a–c using the hypothetical CHW networks in 2016 designed to optimise metrics b–c, and compared these results with the results from the existing networks. The maximum population capacity for CHWs was based on the MOHS norms for the ratio of CHWs per population from the 2021 CHW policy.24 We used the lower bound of the MOHS range for the ratio of CHW per population to be conservative in our estimates: 500 for CHWs in ETR areas and 300 for CHWs in HTR areas. The maximum extent of a catchment was therefore delimited by the maximum travel time of 30 min except in cases where the estimated population in the catchment exceeded the maximum population capacity. In this case, the extent of the catchment was defined by the area containing the estimated population, up to the maximum population capacity.

For (a) we compared the efficiency of deployment of the existing CHW networks with hypothetical networks of the same number of CHWs (n=1521 in ETR areas and n=3650 in HTR areas). We used the MOHS norms for CHWs to population stated above. There is no MOHS range for the ratio of CHW per population to be realistic. For metrics (b) and (c), we based the number of CHW required for the existing CHW networks and the hypothetical CHW networks on the estimated number of CHW needed to cover the estimated population in each catchment using the MOHS norms above. We then compared the estimated geographic coverage attained in ETR areas by the first 1521 CHW of the existing CHW network with the first 1521 CHW of the hypothetical CHW network designed to optimise metrics b–c. We did the same comparison for HTR areas, using the first 3650 CHW of the existing CHW network and first 3650 CHW of the hypothetical CHW network designed to optimise metrics b–c. We assessed the potential effect of uncertainty of the estimates for U5 deaths and *Pf* malaria cases among all ages on interpretation of our efficiency results (see online supplemental appendix 1 and 4).

### RESULTS

#### Accessibility coverage

Three-quarters (76.1%) of the estimated population in 2015 had walking access to a health facility within 60 min (table 1). Accessibility coverage within a 30 min walk to a CHW increased from 16.0% to 80.4% between 2000 and 2015 (table 1). Contrary to current national policy, most of the increase in accessibility coverage of CHWs occurred within 3 km of a health facility where nearly two-thirds (64.5%) of CHWs were deployed. Increases in accessibility coverage were least pronounced in ETR and HTR areas, where only 10.4% and 25.0% of CHWs were deployed, respectively (table 1, online supplemental appendix 1 figure 35). Accessibility coverage of the estimated population in ETR and HTR areas within a 30 min walk to a CHW was 80.9% and 65.4%, respectively, covering an estimated 135 000 and 801 000 people (table 1). Online supplemental video shows the evolution of travel time (walking) to a CHW between 2000 and 2015, indicating a relatively slower scale-up between 2000 and 2010 and a rapid scale-up thereafter—continuing during the Ebola outbreak of 2015–2016. Accessibility coverage within a 30 min walk to a CHW was higher for male CHWs compared with female CHWs, with the disparity most pronounced in ETR and HTR areas (table 1). Accessibility coverage within a 30 min walk varied by training on specific interventions, with the highest accessibility coverage (near 74%) for community case management (CCM) for malaria, prevention and promotion interventions, and CCM index (CCM for malaria plus identification and referral for severe malnutrition) and lower accessibility coverage for reproductive, maternal and newborn health (RMNH) interventions (65.5%) Ebola virus disease signal functions (60.2%) and all packages (48.3%) (table 1). Accessibility coverage also varied by travel scenario, with higher accessibility coverage for dry scenarios versus wet scenarios and walking plus motorised transportation scenarios versus walking scenarios. We provide additional maps in online supplemental appendix 1 figures 2–19 and detailed results at national and subnational levels (chieftdoms) by travel scenario in online supplemental appendix 2, tab ‘Detailed_Results’.

#### Efficiency of deployment

##### ETR areas

The hypothetical CHW network in ETR areas was 43.2% more efficient than the existing network in terms of geographic coverage of the estimated population within a 30 min catchment (97.0% vs 67.7%) (figures 1 and 2A and online supplemental appendix 3, tab ‘Comparison_Pop_ETR’). A majority (53%) of the existing CHW network realised <30% of their maximum population capacity (500), indicating redundancy from inefficient deployment. Additionally, 80% of the estimated population not covered by the existing CHW network in 2015 was concentrated in just 36.6% (56/153) of communes (online supplemental appendix 1 figures 20–22 and 26). The hypothetical CHW network in ETR areas was 27.2% more efficient than the existing network in terms of geographic coverage of the estimated U5 deaths within a 30 min catchment (95.1% vs 74.8%) (figure 2B, online supplemental appendix 3, tab ‘Comparison_U5d_ETR’). The hypothetical CHW network in ETR areas was 26.1% more efficient than the existing network in terms of geographic coverage of the estimated *Pf* malaria
Table 1  Accessibility coverage of the estimated population in 2015 by the health facility and CHW networks, walking scenario

<table>
<thead>
<tr>
<th>Network*</th>
<th>Among population within 3km of a health facility, % within travel time</th>
<th>Among estimated population in ETR areas, % within travel time</th>
<th>Among estimated population in HTR areas, % within travel time</th>
<th>Among total estimated population in 2015, % within travel time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10min</td>
<td>30min</td>
<td>60min</td>
<td>10min</td>
</tr>
<tr>
<td>Health facility</td>
<td></td>
<td></td>
<td></td>
<td>54.8</td>
</tr>
<tr>
<td>CHW</td>
<td>68.0</td>
<td>84.4</td>
<td>96.3</td>
<td>69.5</td>
</tr>
<tr>
<td>CHW in 2000 with preservice training</td>
<td>5.3</td>
<td>20.6</td>
<td>31.0</td>
<td>0.9</td>
</tr>
<tr>
<td>CHW with preservice training</td>
<td>67.9</td>
<td>84.4</td>
<td>96.3</td>
<td>69.5</td>
</tr>
<tr>
<td>Female CHW with preservice training</td>
<td>47.9</td>
<td>63.0</td>
<td>79.8</td>
<td>27.3</td>
</tr>
<tr>
<td>Male CHW with preservice training</td>
<td>60.7</td>
<td>80.6</td>
<td>95.6</td>
<td>62.0</td>
</tr>
<tr>
<td>CHW with preservice training and training on prevention and promotion interventions</td>
<td>60.6</td>
<td>79.3</td>
<td>92.7</td>
<td>61.3</td>
</tr>
<tr>
<td>CHW with preservice training and training on RMNH interventions</td>
<td>53.5</td>
<td>71.5</td>
<td>87.0</td>
<td>41.7</td>
</tr>
<tr>
<td>CHW with preservice training and training on CCM for malaria</td>
<td>61.9</td>
<td>79.5</td>
<td>91.5</td>
<td>63.7</td>
</tr>
<tr>
<td>CHW with preservice training and training on CCM index</td>
<td>60.9</td>
<td>78.7</td>
<td>90.8</td>
<td>62.6</td>
</tr>
<tr>
<td>CHW with preservice training and training on EVD signal functions</td>
<td>48.9</td>
<td>67.7</td>
<td>84.0</td>
<td>33.3</td>
</tr>
<tr>
<td>CHW with preservice training and training on all packages</td>
<td>38.3</td>
<td>56.3</td>
<td>71.5</td>
<td>20.9</td>
</tr>
</tbody>
</table>

*Results for the health facility network are as of May 2016. Results for the CHW networks are as of February 2016, except where noted (row three is for CHWs in the year 2000 that had preservice training).

CCM, community case management; CHW, community health worker; ETR, easy-to-reach area; EVD, Ebola virus disease; RMNH, reproductive, maternal, newborn health.
Figure 1  Modelled catchment areas of the existing CHW network in ETR areas, and hypothetical optimised CHW network in ETR areas in 2016 at 1 km×1 km resolution. (A) Modelled 30 min catchment areas of the existing CHW network (blue) in ETR areas in 2016; (B) modelled 30 min catchment areas of the hypothetical optimised CHW network (pink) in ETR areas in 2016. All analyses at 1 km×1 km resolution based on a walking scenario and maximum population capacity of the given network. Images depict chiefdoms within Kambia and Port Loko districts in Northern province. *For visualisation purposes, road classes limited to motorway, trunk, primary, secondary and tertiary. CHW, community health worker; ETR, easy-to-reach area.

Figure 2  Efficiency of deployment of the existing CHW network compared with hypothetical optimised CHW networks in ETR areas at 1 km×1 km resolution. (A) Comparison of the per cent of the estimated population in ETR areas covered within a 30 min catchment area (walking) by the existing CHW network compared with a hypothetical CHW network deployed to optimise geographic coverage of the estimated population in ETR areas; (B) comparison of the per cent of the estimated U5 deaths in ETR areas covered within a 30 min catchment area (walking) by the existing CHW network compared with a hypothetical CHW network deployed to optimise geographic coverage of the estimated U5 deaths in ETR areas; (C) comparison of the per cent of the estimated Pf malaria cases among all ages (0–99 years) in ETR areas that was covered within a 30 min catchment area (walking) by the existing CHW network compared with a hypothetical CHW network deployed to optimise geographic coverage of the estimated Pf malaria cases among all ages (0–99 years) in ETR areas. All analyses at 1 km×1 km resolution. CHW, community health worker; ETR, easy-to-reach area; Pf, Plasmodium falciparum; U5, under-five.
cases (all ages) within a 30 min catchment (97.1% vs 77.0%) (figure 2C, online supplemental appendix 3, tab ‘Comparison_Cases_ETR’).

HTR areas
The hypothetical CHW network in HTR areas was 71.9% more efficient than the existing network in terms of geographic coverage of the estimated population within a 30 min catchment (78.3% vs 45.5%) (figures 3 and 4A and online supplemental appendix 3, tab ‘Comparison_Pop_HTR’). Nearly half (47%) of the existing CHW network in HTR realised <30% of their maximum population capacity (300), indicating redundancy from inefficient deployment. Additionally, 80% of the estimated population not covered by the existing CHW network in 2015 was concentrated in just 37.2% (57/153) of communes (online supplemental appendix 1 figures 23–25). The hypothetical CHW network in HTR areas was 38.9% more efficient than the existing network in terms of geographic coverage of the estimated P f malaria cases (all ages) within a 30 min catchment (79.7% vs 65.1%) (figure 4C, online supplemental appendix 3, tab ‘Comparison_Cases_HTR’).

DISCUSSION
This was the first study to assess geographical accessibility and efficiency of deployment of CHWs at national scale in Sierra Leone. Accessibility coverage of CHWs increased between 2000 and 2015 but most of the increase occurred within 3 km of a health facility, contrary to current national policy. ETR and HTR areas were less well covered by CHWs. There was substantial variation in access to a CHW across subnational geographies. Access to female CHWs was lower than male CHWs. Access to CHWs trained on RMNH interventions was lower than access to CHWs trained on prevention and promotion interventions or community case management for malaria. Optimised CHW networks in ETR and HTR areas were more efficiently deployed than existing networks by 26.1%–43.2% and 22.4%–71.9%, respectively, depending on targeting metric.

Implications for policy
Planning for the scale-up and efficient deployment of the CHW workforce, like with broader HRH and health sector planning, cannot be addressed purely through modelling. The political economy of such planning is complex, involving multiple factors that are difficult to capture in models. That said, modelling can be a useful tool among others, for policy makers and planners. Below we outline the implications of our analysis for policy makers and planners in Sierra Leone, as well as other countries in sub-Saharan Africa with similar contexts and interest in optimising PHC at community level.

First, scale-up of CHWs improved geographical accessibility of PHC at community level between 2000 and 2015 but most of the increase occurred within 3 km of a health facility, where a majority of CHWs were deployed. This pattern broadly reflects the population distribution—77.2% of the population in 2015 were within 3 km of a health facility—this is similar to the urban skew of the broader HRH workforce and reflects early CHW policy (prior to 2016, CHW could be selected from and work in communities regardless of proximity to health facilities). But it does not align with current national policy and
therefore warrants rethinking. With the 2021–2025 CHW policy, the MOHS plans to rightsize and retarget the CHW workforce (including CHW peer supervisors) by reducing it by 40% and retargeting CHW recruitment and deployment towards ETR and HTR areas. This is a bold move to optimise scale and deployment of CHWs in the context of broader efforts to optimise HRH deployment. This key shift was informed by an earlier iteration of our current analysis, which was included in an assessment of the National CHW Programme by JSI and broader CHW policy discussions. Our current analysis supports this important policy decision by the MOHS. However, optimising scale and deployment of CHWs comes with operational challenges. For example, employers will need to end the employment of CHWs and CHW peer supervisors located within 3 km of a health facility. Affected workers should be compensated fairly for early termination of their employment. Planners should anticipate the need to engage affected communities to regain their trust. Similarly, new CHWs and CHW peer supervisors will need to be recruited from communities in ETR and HTR areas not already adequately covered. They will need to be trained, paid, supervised and supported. This will require effective planning, coordination, logistics and resources. But on balance, the positives outweigh the negatives. We estimate the cost-savings from the planned rightsizing and retargeting of the CHW workforce to be approximately US$3.8 million annually (40% of the current annual cost of US$9.5 million). Cost-savings could be re-directed towards professionalising the CHW workforce and strengthening the health system and community enablers needed to optimise CHW performance, which have been well described to have major shortfalls in Sierra Leone and most national CHW programmes.

Second, our analysis highlighted an important gender disparity in CHW deployment (35% of CHWs were female and 65% were male). This gender disparity may negatively impact the use of specific services (e.g., interventions for sexual health, RMNH). The MOHS intends to address this gender disparity in implementation of the 2021–2025 CHW policy, shifting the gender distribution to 60% female and 40% male. This would be an important shift from an HRH gender equity lens. It could improve the use of interventions such as those noted above. Lastly, it would contribute to greater gender balance in the CHW workforce.

![Figure 4](http://gh.bmj.com/)

**Figure 4** Efficiency of deployment of the existing CHW network compared with hypothetical optimised CHW networks in HTR areas at 1 km×1 km resolution. (A) Comparison of the per cent of the estimated population in HTR areas covered within a 30 min catchment area (walking) by the existing CHW network compared with a hypothetical CHW network deployed to optimise geographic coverage of the estimated population in HTR areas; (B) comparison of the per cent of the estimated U5 deaths in HTR areas covered within a 30 min catchment area (walking) by the existing CHW network compared with a hypothetical CHW network deployed to optimise geographic coverage of the estimated U5 deaths in HTR areas; (C) comparison of the per cent of the estimated Pf malaria cases among all ages (0–99 years) in HTR areas that was covered within a 30 min catchment area (walking) by the existing CHW network compared with a hypothetical CHW network deployed to optimise geographic coverage of the estimated Pf malaria cases among all ages (0–99 years) in HTR areas. All analyses at 1 km×1 km resolution. CHW, community health worker; HTR, hard-to-reach area; Pf, Plasmodium falciparum; U5, under-five.
Regarding the gender disparities identified, nearly all CHWs self-reported that they received preservice training but there was large variation in terms of training on specific services, indicating that the standard MOHS preservice training may not have been systematically implemented. The MOHS may need to strengthen coordination and oversight of the implementation of the standard MOHS preservice training as well as in-service training. This could be aided by updating and maintaining the national georeferenced CHWML hosted within or linked to the national human resources for health information system—iHRIS—and using the CHWML as the basis for tracking, planning and coordinating training.

Fourth, the current focus of the MOHS on rightsizing and retargeting the CHW workforce could enable future discussions on a sustainable financing pathway for CHWs, inclusive of increasing government financing for CHWs and a pathway for integration of CHWs within the civil service.

**Limitations**

There are several important limitations of our study. First, our analysis is limited by the completeness and quality of the publicly available road and river network data. We acknowledge that more complete and/or higher quality data on roads and rivers may be available outside the public domain. We acknowledge that not all rivers may be perennial barriers to movement, particularly where bridges exist. We attempted to mitigate this limitation by allowing major road classes to cross rivers. Second, our analysis does not account for uncertainty of the estimates of population counts, limiting our ability to account for this source of uncertainty in measures of physical accessibility to services. Estimates of the uncertainty of the estimated population counts in Sierra Leone for the years 2000–2015 were not available, but we acknowledge that availability of this kind of data will be important for improving future modelling efforts. Third, the estimated population counts for 2000–2014 use the 2015 population settlement footprint from 2015, which may not accurately reflect the population settlement footprint for the period 2000–2014. Fourth, our analysis is based on estimated travel speeds from other studies in sub-Saharan Africa, not empirical data from Sierra Leone or local expert knowledge, although research indicates these speeds may be appropriate in the Sierra Leone context. Our analysis does not account for uncertainty of travel speed estimates.

Additionally, our analysis does not account for variation in walking speeds or common modes of transportation used across population groups. For example, pregnant women, people with illness, caregivers of ill children, the elderly population, people with disabilities may walk slower than the general population, modes of transport may differ by socioeconomic status and boat travel may be important in certain geographic areas. A planned update to this analysis in 2021–2022 will attempt to address the limitations above regarding travel speeds and modes of transportation by incorporating information derived from subnational level workshops with local experts. Fifth, our analysis used CHW self-reported data on receipt of training and year of deployment, which may be subject to recall bias. Sixth, our analysis did not account for the possibility of accessing health services across national boundaries, an important consideration for border communities and migrant populations.

We acknowledge that there are many factors beyond physical accessibility that affect access to and use of health services, such as social and economic barriers to care seeking. Such factors may impact access to and use of health services independently of physical accessibility or through interactions with physical accessibility. It is also important to consider quality of services, including population perceptions of the quality of services, and the potential for bypassing.

We also acknowledge that this kind of modelling can be challenging. Integration into national processes and policy takes time and requires strengthening national institutional capacity. Additionally, operationalising the optimised deployment poses many challenges as noted above. But despite these challenges, this kind of modelling can be very useful as we have demonstrated in the case of Sierra Leone. At the time of writing, coauthors—including those from the MOHS—were updating this analysis with datasets from 2021, with a view of fine-tuning implementation of the 2021–2025 CHW policy and informing updates to broader HRH and health sector development plans and strategies.

**CONCLUSION**

Geographical accessibility of PHC services at community level improved in Sierra Leone between 2000 and 2015 through the scale-up of CHWs. However, the scale and deployment of the CHW network no longer aligns with current national policy. The new CHW policy for 2021–2025 calls for a rightsizing and retargeting of the CHW network and our analysis supports this policy decision by identifying important inefficiencies of scale and deployment. Countries in sub-Saharan Africa with similar interest in optimising scale and deployment of their CHW workforce in the context of broader HRH and health sector planning may look to Sierra Leone as an exemplar model from which to learn.
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Supplementary Appendix 1

This file provides supplementary figures, tables, and methods for Oliphant NP, Ray N, Curtis A et al. Optimising scale and deployment of community health workers in Sierra Leone: a geospatial analysis. 2022.
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Supplementary Figure 1. Simplified analysis flow diagram

(A) Analysis flow for preparation of estimated population layers 2000-2015, estimated U5 deaths layers, and estimated $P_f$ malaria cases layers. (B) Analysis flow for estimates and maps of geographic accessibility. (C) Analysis flow for estimates and maps of geographic coverage of the estimated population in 2015 by the PHU network. (D) Analysis flow for estimates and maps of geographic coverage of ETR and HTR populations in 2015 by the existing CHW network in ETR and HTR areas. (E) Analysis flow for estimates and maps of geographic coverage of the estimated ETR and HTR populations in 2015 by the existing CHW network in ETR and HTR areas.
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bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.
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Supplementary Figure 10. Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest CHW in 2016 with pre-service training and trained on RMNH interventions. CHW in 2016 with pre-service training and trained on an index of reproductive, maternal and newborn health (RMNH) interventions, n=9107. RMNH interventions included promotion of ANC, birth readiness and preparedness, promotion of delivery in facility, postnatal care for the mother, postnatal care for the newborn, identification of danger signs during pregnancy, identification of danger signs for mothers during the postnatal period, identification of danger signs for newborns during the postnatal period, and family planning methods. CHW=community health worker.

*For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.
Supplementary Figure 11. Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest CHW in 2016 with pre-service training and trained on CCM for malaria. CHW in 2016 with pre-service training and trained on community case management (CCM) for malaria, n=11947. Note the question in the 2016 national georeferenced census of CHWs was “Have you completed training on identification and treatment of common childhood illnesses (pneumonia, diarrhoea and malaria)?” Based on knowledge of the scale of training of CHWs on CCM for malaria and integrated community case management (iCCM) for pneumonia, diarrhoea and malaria, the consensus of national MOHS and UNICEF staff was that results from this question reflected training on CCM for malaria, not iCCM for pneumonia, diarrhoea, and malaria. CHW=community health worker. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.
Supplementary Figure 12. Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest CHW in 2016 with pre-service training and trained on CCM for malaria and identification and referral of severe malnutrition. CHW in 2016 with pre-service training and trained on community case management (CCM) for malaria and identification and referral of severe malnutrition, n=11604. For the CCM malaria component, the question in the 2016 national georeferenced census of CHWs was “Have you completed training on identification and treatment of common childhood illnesses (pneumonia, diarrhoea and malaria)?” Based on knowledge of the scale of training of CHWs on CCM for malaria and integrated community case management (iCCM) for pneumonia, diarrhoea and malaria, the consensus of national MOHS and UNICEF staff was that results from this question reflected training on CCM for malaria, not iCCM for pneumonia, diarrhoea, and malaria. CHW=community health worker. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.
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Supplementary Figure 17. Geographic accessibility (travel time in minutes, walking + motorised transportation in dry conditions) to the nearest CHW in 2016. Community health workers (CHW) in 2016, n=14579. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.
Supplementary Figure 18. Geographic accessibility (travel time in minutes, walking in wet conditions) to the nearest CHW in 2016. Community health workers (CHW) in 2016, n=14579. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.
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Supplementary Figure 20. Median and interquartile range of geographic coverage at chiefdom level (administrative level 3) of the estimated population in ETR areas by the existing network of CHWs, by district (administrative level 2). Median and interquartile range of geographic coverage at chiefdom level (administrative level 3) of the estimated population in ETR areas covered by the existing CHW network (30-minute catchment, walking scenario) by district (administrative level 2). Red line at national geographic coverage of 72.0% of the estimated population in ETR areas. ETR=easy to reach. CHW=community health worker.
Supplementary Figure 21. Estimated population in ETR areas in 2015 not covered by the CHW network (30-minute catchment, walking) by chiefdom (administrative level 3). ETR=easy to reach. CHW=community health worker. Eight chiefdoms without ETR areas coloured white and excluded from analysis. Total districts = 153.
Supplementary Figure 22. Chiefdoms contributing to 80% of the estimated population in ETR not covered by the CHW network in 2016 (30-minute catchment, walking). ETR=easy to reach. CHW=community health worker. Eight chiefdoms without ETR areas coloured white and excluded from analysis. Total districts = 153.
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Supplementary Figure 24. Estimated population in HTR areas not covered by the CHW network in 2016 (30-minute catchment, walking) by chiefdom (administrative level 3). HTR=hard to reach. CHW=community health worker. Two chiefdoms without HTR areas coloured white and excluded from analysis. Total districts = 153.
Supplementary Figure 25. Chiefdoms contributing to 80% of the estimated population in HTR not covered by the CHW network in 2016 (30-minute catchment, walking). HTR=hard to reach. CHW=community health worker. Two chiefdoms without HTR areas coloured white and excluded from analysis. Total districts = 153.
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Supplementary Figure 27. Digital elevation model at 100m x 100m resolution. NASA SRTMGL1 version 003 (approximately 30m x 30m), resampled to 100m x 100m and 1km x 1km (later not shown). Accessed 13 August 2017.
Supplementary Figure 28. Estimated population count in 2015 per grid cell at 100m x 100m resolution.

Population layers produced at 100m x 100m resolution and 1km x 1km resolution resampled from Worldpop census disaggregated gridded population estimates at approximated 90m x 90m resolution for Sierra Leone in 2015, version 2.0. Worldpop.
Supplementary Figure 29. Estimated population count in easy to reach (ETR) areas in 2015 per grid cell at 1km x 1km resolution.

Population layers produced at 1km x 1km resolution resampled from Worldpop census disaggregated gridded population estimates at approximated 90m x 90m resolution for Sierra Leone in 2015, version 2.0 and clipped to the footprint of ETR areas. Source: Derived from WorldPop and Statistics Sierra Leone. 2021. Census disaggregated gridded population estimates for Sierra Leone (2015), version 2.0. University of Southampton.² Health facilities include: hospitals, CHC, CHP, MCHP, and clinics. Travel time to a health facility derived from geographic accessibility analysis of the health facility network at 1km resolution.
Supplementary Figure 30. Estimated population count in easy to reach (HTR) areas in 2015 per grid cell at 1km x 1km resolution.

Population layers produced at 1km x 1km resolution resampled from Worldpop census disaggregated gridded population estimates at approximated 90m x 90m resolution for Sierra Leone in 2015, version 2.0 and clipped to the footprint of HTR areas. Source: Derived from WorldPop and Statistics Sierra Leone. 2021. Census disaggregated gridded population estimates for Sierra Leone (2015), version 2.0. University of Southampton. Health facilities include: hospitals, CHC, CHP, MCHP, and clinics. Travel time to a health facility derived from geographic accessibility analysis of the health facility network at 1km resolution.
Supplementary Figure 31. Mean count of U5 deaths in 2015 per grid cell at 1km x 1km.
Mean count of U5 deaths in 2015 at 1km x 1km derived from the mean U5 mortality rate in 2015 (IHME) at 5km x 5km, resampled to 1km x 1km and multiplied by the infant population in 2015 (Worldpop) at 1km x 1km.
Supplementary Figure 32. Estimated Pf malaria cases among all ages (0-99 years) in 2015 per grid cell at 1km x 1km resolution.

Annual mean incidence of Plasmodium falciparum (Pf) malaria among all ages (0-99 years) in 2015 globally at 2.5 arcminutes (approximately 5km x 5km) resolution from Weiss et al 2019^4, reprojected to 1km x 1km resolution and multiplied by the estimated population in 2015^7 (see Methods).
Supplementary Figure 33. Road network
HOTOSM Sierra Leone Roads (OpenStreetMapExport)
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Supplementary Figure 35. Land cover at 100m x 100m resolution. Land cover at 100m x 100m and 1km x 1km resolutions (latter not shown). Discreet land cover classes are based on the UN Land Cover Classification System (LCCS).
Supplementary Figure 36. **Merged land cover at 100m x 100m resolution.** Merged land cover at 100m x 100m and 1km x 1km resolutions (latter not shown) derived using the Merge land cover tool in Accessmod 5.6.56.
Supplementary Figure 37. PHUs and CHWs. Source health facilities: 2016 Master Facility List\(^9\) derived from the following three sources: 1) the 2015 Health Facility Assessment (census) by the Ministry of Health and Sanitation, Sierra Leone and UNICEF; 2) The 2015-2016 Georeferenced Census of PHUs by the Ministry of Health and Sanitation, Sierra Leone and UNICEF; 3) the 2016 Health Facility Assessment (census) by CHAI.
Source CHWs: 2016 Master CHW List\(^10\) derived from the 2015-2016 Georeferenced Census of CHWs by the Ministry of Health and Sanitation, Sierra Leone and UNICEF.
Supplementary Figure 38. Health system pyramid and health service delivery networks included in analysis. PHU=Peripheral Health Unit; MCHP = maternal and child health post; CHP = community health post; CHC = community health centre; CHW = community health worker; DHMT = district health management team; PHC = primary health care. Source health facilities: 2016 Master Facility List derived from the following three sources: 1) the 2015 Health Facility Assessment (census) by the Ministry of Health and Sanitation, Sierra Leone and UNICEF; 2) The 2015-2016 Georeferenced Census of PHUs by the Ministry of Health and Sanitation, Sierra Leone and UNICEF; 3) the 2016 Health Facility Assessment (census) by CHAI.

Source CHWs: 2016 Master CHW List derived from the 2015-2016 Georeferenced Census of CHWs by the Ministry of Health and Sanitation, Sierra Leone and UNICEF.

Data

Administrative boundaries

We obtained vector shapefiles for administrative boundaries 0-3 developed from the GADM database (www.gadm.org), version 3.4, April 15, 2018. We reprojected the shapefiles for the administrative boundaries 0-3 from the Coordinate Reference System (CRS) EPSG:4326, WGS 84 to the CRS EPSG:2161 - Sierra Leone 1968 / UTM zone 28N – Projected using the GDAL “Warp” tool in QGIS 3.18.2-Zürich.

Health system pyramid and health service delivery networks

During the period of focus of this study, 2000-2016, the Ministry of Health and Sanitation (MOHS) provided overall leadership, governance, and coordination of the health sector. Each district was supported by a district health management team (DHMT) responsible for management and supervision of the hospitals and other health facilities, collectively known as peripheral health units (PHUs), within the boundaries of the district, as well as serving as a link between the primary level and the central level of the MOHS. Hospitals and health facilities were staffed with frontline health workers and managed by a hospital administrator or PHU manager.

The health system included public, private, and non-governmental / faith-based sectors organised in a decentralised, pyramidal structure with three administrative levels: a tertiary level, a secondary level, and a primary level. The tertiary level was comprised of national specialty and teaching hospitals located in the national capital, Freetown,
providing specialty care and referral services from the secondary level. According to national norms, tertiary hospitals had a maximum population capacity of 500000.14,15

The secondary level was comprised of secondary referral hospitals (including public sector regional and district hospitals and some private sector and non-governmental / faith-based organization hospitals) typically located in district capitals or regional hubs and staffed by doctors, nurses and laboratory technicians providing a package of primary health care services, known as the basic package of essential health services (BPEHS), and referral services from the primary level, with at least one public sector hospital per district providing Comprehensive Emergency Obstetric and Newborn Care (CEmONC). According to national norms, regional and district hospitals had a maximum population capacity of 500000.14,15

The primary level was comprised of public sector peripheral health units (PHUs) providing primary health care services per the BPEHS. PHUs – in descending order according to size and availability of skilled health care workers – included community health centre (CHCs) community health posts (CHPs) staffed by clinical health assistants (CHAs), and maternal and child health posts (MCHPs). CHCs were typically located in densely populated areas of the chiefdom headquarter town and staffed by a Community Health Officer (CHO), Community Health Assistant (CHA), community health nurses, midwives, maternal and child health (MCH) aids and other clinical and support staff. According to national norms, CHC had a maximum population capacity of 10000-30000. The CHC was responsible for supervision of CHPs and MCHPs within its catchment area. CHPs were typically located in a town and staffed by community health nurse and CHA, with the latter typically serving as the CHP manager. According to national norms, CHPs had a maximum population capacity of 5000-10000. MCHPs were the most peripheral PHU and focused on MCH services. MCHPs were staffed by MCH aides. According to national norms, MCHPs had a maximum population capacity of 500-5000. The primary level also included private sector clinics providing primary health care services.

At the base of the primary level were CHWs providing community-based primary health care services, including prevention, promotion, and curative services, as well as conducting surveillance activities. CHW policy evolved over time, including major policy developments in 2012,16 201617 and, more recently in 2021.18

The following summarises points from the CHW policy of 2012 relevant to our analysis:

- **Definition:** The MOHS defined CHWs as “a community member who is selected by the community and will be trained to provide basic essential health services and information at community level.” Several cadres of service providers at community level existed in 2012 (e.g., traditional birth attendants or TBAs, community drug distributors or CDDs, community-based distributors of contraceptives or CBDS, community-based providers or CBPs, blue flag volunteers, red cross volunteers, and community owned resource persons or CORPs). According to the 2012 CHW policy, community members of these cadres that underwent a standardised 10-day training by the MOHS and met the above definition for a CHW were recognised as CHWs.

- **Package of services:** The package of services CHWs could provide was standardised and defined by the MOHS and included a focus on basic primary health care services, including prevention, promotion, and curative services. This included household visits to promote reproductive, maternal, newborn and child health and nutrition interventions, water and sanitation interventions, integrated community case management of diarrhoea, pneumonia, and malaria for children under-five, screening for acute malnutrition among children under-five, malaria case management services for children above five years of age and adults, monitoring of vital events such as births and deaths, disease surveillance

- **Selection:** CHWs should be selected by the community they serve, using standardised selection criteria set by the MOHS, and the selection process should ensure gender parity.

- **Training:** The 2012 CHW policy includes standards for CHW training, including the 10-day standardised MOHS training, additional modular training, specifies the need to use clear selection criteria to identify the most appropriate CHWs for additional training and quality assurance of additional training.

- **Certification:** The 2012 CHW policy indicates that CHW completing the standardised 10-day MOHS training should receive a certificate of participation but lacks details on how certification is verified.
• Deployment: The 2012 CHW policy did not include criteria/restrictions for geographic deployment of CHWs (i.e., they could be selected from and work in communities regardless of proximity to PHUs).
• CHW to population ratio: 1 CHW per 100-500 population
• Remuneration: CHWs were volunteers but recommended they be provided with a minimum motivation package of monetary and non-monetary incentives – however the monetary portion of the minimum package was not defined. In practice, CHWs were employed by non-governmental organizations (NGOs) but remuneration was not harmonised across NGOs.
• Supervision: CHWs were attached to the nearest PHU and supervised by the PHU in-charge.

The following summarises updates to CHW policy that occurred in 2016 and 2021 that are relevant to our analysis:

• Definition: The definition of CHWs remained the same as in the 2012 CHW policy, however the 2016 CHW policy added text detailing the circumstances in which a community-based provider/program could operate outside of the national CHW program. The definition of a CHW in the 2021 CHW policy follows the definition of the 2012 and 2016 policy, but provides further detail on the CHW status as a lay health worker and their scope of work: “A community-based Lay Health Worker trained and deployed by MoHS to provide promotive, preventive, limited basic curative and referral services in relation to reproductive, maternal, newborn, child, adolescent health, and nutrition (RMNCAH-N), communicable and non-communicable diseases in his/her community”. Additionally, the 2021 CHW policy includes a section on harmonization and integration of CHWs, stipulating the requirement to integrate all CHW cadres (including those supported by vertical programs such as TB/HIV and malaria) into the national CHW program and harmonization/standardization of the roles, responsibilities and governance of the CHWs.

• Package of services: In the 2016 CHW policy, the package of services remained largely the same as 2012 but detail was expanded for RMNCH (e.g. included counselling on HIV testing among women and their spouses), management of diarrhoea was expanded to children over five years of age (this expansion of iCCM in addition to case management for malaria among the population over five years of age was called “iCCM plus”), a broader focus on disease prevention and control, including community-based surveillance, and community sensitization on the signs, symptoms and risk factors for HIV and TB was added. In the 2021 CHW policy, the scope of work for CHWs was differentiated between CHWs in ETR areas and CHWs in HTR areas. CHWs in HTR areas provide the full scope of work, including iCCM plus, TB and HIV services. CHWs in ETR areas provide all services except treatment services as part of iCCM plus (rather than treat, they refer sick people to health facilities) and provide TB and HIV services per the scope of work. Details on the scope of work for TB and HIV was expanded in the 2021 CHW policy (e.g., on TB screening and referral of suspected TB cases, treatment adherence support for HIV and TB). The 2021 CHW policy also added non-communicable diseases, mental health, and community preparedness for emerging disease prevention and control, including preparedness for COVID-19 vaccination.

• Selection: Selection criteria remained the same as in the 2012 CHW policy, however the 2016 policy added text on the selection process and processes for removal and replacement of CHWs. No major changes in the 2021 CHW policy.

• Training: In the 2016 CHW policy, a section devoted to CHW training (pre-service and in-service) was added, including an annex with details on the pre-service training curriculum. The training curriculum was further standardised and expanded to include the interventions added since 2012. The 2016 CHW policy explicitly noted that the training curriculum was competency- and skills-based. It also added text on training of peer supervisors, PHU supervisors, and chiefdom supervisors. The 2021 CHW policy also added training on specific HIV and TB services, non-communicable diseases, mental health, and community preparedness for emerging disease prevention and control, including preparedness for COVID-19 vaccination to the standard training curriculum.

• Certification: The 2016 CHW policy stipulates that DHMTs must provide CHWs that meet the criteria for being a CHW within the national program with certificates and ID cards. The 2021 CHW policy includes a specific section on the certification process of CHWs i.e., verification of completion of the standard pre-service training package and that the CHW meets standards to fulfil their roles and responsibilities.
• Deployment: The 2016 CHW policy introduced definitions for easy to reach (ETR) areas and hard to reach (HTR) areas. ETR areas were defined as areas within a 3km radius of a PHU. HTR areas were defined as areas beyond a 3km radius of a PHU or in a difficult geographical area as determined by the DHMT. The 2021 CHW policy refined these definitions. ETR areas were redefined as areas within a 3km-5km radius of a PHU. HTR were redefined as areas beyond 5km of a PHU or within a 3km-5km radius of a PHU with difficult terrain (“difficult terrain” was not explicitly defined). The 2021 CHW policy also stipulated that CHW within 3km radius of a PHU would no longer be supported.

• CHW to population ratio: In 2021 the CHW to population ratio was updated to 1 CHW per 500-1000 population in ETR areas and 1 CHW per 300-350 population in HTR areas

• Remuneration: The 2016 CHW policy revised the financial and non-financial incentives for CHWs. Notably a defined a minimum financial incentive of Le 100,000 per month was established for all CHWs. In addition, CHWs in ETR were to receive Le 50,000 for transport, phone top-ups and logistical support. In the 2021 CHW policy incentives for CHWs in ETR areas (revised per above) remained at Le 100,000 per month while incentives for CHW in HTR areas increased to Le 200,000 per month; additionally, the incentives for transport, phone top-ups and logistics support for CHW in ETR areas was maintained at Le 50,000 per month for CHW in ETR while those incentives for CHWs in HTR areas increased to Le80,000 per month. In practice, CHWs were employed by NGOs. CHW contracts included harmonised financial remuneration, as noted above.

• Supervision: The 2016 CHW policy stipulates that CHWs are supervised by PHU in-charges however, in recognition of constraints on regular supervision by health facility staff due to staff shortages at some health facilities, the MOHS introduced the concept of peer supervisors – “community members who have more education and skills than CHWs, supports but does not replace PHU supervision” (ref). Supervision by PHU in-charges and peer supervisors was complemented by supervision by chiefdom supervisors from the CHC catchment in which the CHW worked, implementing partner staff, DHMTs, district level CHW focal persons, regional CHW coordinators and the national CHW Hub. No major changes to supervision were included in the 2021 CHW policy.

As of 2016, there were three tertiary level hospitals (all with geographic coordinates and all public), 32 secondary level hospitals (all with geographic coordinates, including 14 public sector district hospitals), 1206 PHUs (all with GPS coordinates, including 603 MCHP, 356 CHP, 229 CHC and 18 clinics) and 14632 working CHWs, including 14579 CHWs with geographic coordinates of the main settlement in which they work of which 14494 had received the standard 10-day pre-service training of the MOHS.

Health facility network

Through a data sharing agreement with UNICEF, we obtained the 2016 master facility list (MFL) in the form of a vector point shapefile dataset in the CRS EPSG:4326, WGS 84 with the global positioning system (GPS) coordinates and basic identification information for public and private health facilities, including 35 hospitals, 229 CHCs, 356 CHPs, 603 MCHPs and 18 clinics (see Supplementary Figure 18). We reprojected the MFL shapefile to the CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N, using the GDAL “Warp” tool in QGIS 3.18.2 Zürich. For our analysis of geographic coverage, national norms (mid-point in the case of a range) were used to inform the maximum population capacity of each health facility type: 500000 for hospitals, 20000 for CHCs, 7500 for CHPs, 2500 for MCHPs, and 2500 for clinics.

CHW network

We obtained, through a data sharing agreement with UNICEF, the 2016 CHW master list (CHWML) – derived from the 2015-2016 georeferenced census of CHWs in the form of a vector point shapefile dataset in the CRS EPSG:4326, WGS 84 with the global positioning system (GPS) coordinates of the CHW’s primary place of work (note: since the main modality of service delivery by the CHWs was home visits and CHWs did not provide services from a fixed location within a settlement, the primary place of work was taken as a central square or landmark within the primary human settlement within which the CHW worked). The CHWML also contained data elements essential for our analysis for all CHWs, including self-reported data on CHW gender, training (whether the CHW...
received the standard MOHS 10 day pre-service training and whether they received training on specific interventions), and year the CHW was deployed (started working). As of the March 2016, there were 14632 working CHWs per the 2015-2016 georeferenced census of CHWs. Of these, the CHWML included geographic coordinates of the settlement in which CHWs were deployed for 14579 CHWs. Of these, 14494 had received the standard 10-day pre-service training of the MOHS (see Supplementary Figure 18). We reprojected the CHWML shapefile to the CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N, using the GDAL “Warp” tool in QGIS 3.18.2 Zürich. For our analysis of geographic coverage and efficiency, national norms from the 2021 CHW policy (lower-bound of the range for CHW in ETR areas and CHW in HTR areas to ensure a conservative analysis from a public health perspective) were used to inform the maximum population capacity of each CHW in ETR areas and HTR areas.

ETR areas and HTR areas

For our efficiency analysis we prepared dummy raster files at 1km resolution representing ETR areas and HTR areas (see Supplementary Figures 12-13 for the analysis flow).

For ETR areas, we used the following steps:

1. We conducted a buffer analysis to produce a vector shapefile of the area 3-5km from health facility and rasterised the vector shapefile at 1km resolution using the “Rasterise” function in QGIS 3.18.2 Zürich.
2. We created a raster for the travel time walking to the nearest health facility at 1km resolution using the “Accessibility” module within Accessmod 5.6.56, using the merged land cover as the merged land cover input, the health facility network (including hospitals, CHCs, CHPs, MCHPs, and clinics) as the health facility input, and 0 as the maximum travel time (effectively allowing the travel time analysis to run to the full extent of the merged land cover layer). We then clipped the resulting travel time raster to cells within a 60-minute walk in dry conditions of health facilities.
3. We created a new dummy raster of the cells in ETR areas [r_SLE_ETR_1km] defined as cells that were 3-5km from a health facility (from step 1 above) AND less than 60 minutes walking from a health facility in 2016 (from step 2 above), at 1km resolution using the “Raster calculator” function in QGIS 3.18.2 Zürich.

For HTR areas, we used the following steps:

1. We created a raster for cells beyond 60 minutes walking in dry conditions from a health facility in 2016 by clipping the travel time raster from step 2 above to cells beyond 60 minutes walking in dry conditions from a health facility from a health facility in 2016 using the “Raster calculator” function in QGIS 3.18.2 Zürich.
2. We conducted a buffer analysis to produce a vector shapefile of the area beyond 5km from health facility and rasterised the vector shapefile at 1km resolution using the “Rasterise” function in QGIS 3.18.2 Zürich.
3. We created a new dummy raster of the cells in HTR areas [r_SLE_HTR_1km] defined as cells that were 3-5km from a health facility OR beyond 60 minutes from a health facility in 2016 OR beyond 5km from a health facility in 2016 at 1km resolution using the “Raster calculator” function in QGIS 3.18.2 Zürich.

Optimised CHW networks for ETR areas and HTR areas

For our efficiency analysis we prepared three vector point shapefiles for hypothetical CHW networks for ETR areas and HTR areas (see section below on production of ETR areas and HTR areas), thus six vector point shapefiles in total): 1) optimising geographic coverage of the estimated population in ETR areas in 2015 (and the same for HTR areas) 2) optimising geographic coverage of the estimated under-five deaths in ETR areas in 2015 (and the same for HTR areas) and 3) optimising geographic coverage of the estimated Pf malaria cases among all ages (0-99) in ETR areas in 2015 (and the same for HTR areas), given the same number of CHW as the existing CHW network in ETR areas and HTR areas, at 1km x 1km resolution.

For ETR areas, we used the following steps:
1. We created a raster of the estimated population in 2015 in ETR cells by multiplying the estimated population count in 2015 at 1km resolution by the dummy raster for ETR areas (see section above on preparation of ETR areas) at 1km resolution, using the “Raster calculator” function in QGIS 3.18.2 Zürich.12
2. To identify candidate cells for the hypothetical CHW network in ETR cells, we created a raster at 1km resolution containing cells where the estimated population in 2015 in ETR cells was at least 30 people using the “Raster calculator” function in QGIS 3.18.2 Zürich.12
3. We created a vector point layer from the raster in step 2 above using the “Raster pixels to points” function in QGIS 3.18.2 Zürich.12 The resulting vector point layer contained point features at the centroid of every cell at 1km resolution where the estimated population in 2015 in ETR areas was at least 30 people, resulting in 1677 candidate sites for the hypothetical CHW network in ETR areas.

For HTR areas, we used the following steps:

1. We created a raster of the estimated population in 2015 in HTR cells by multiplying the estimated population count in 2015 at 1km resolution by the dummy raster for HTR (see section above on preparation of HTR areas) at 1km resolution, using the “Raster calculator” function in QGIS 3.18.2 Zürich.12
2. To identify candidate cells for the hypothetical CHW network in HTR cells, we created a raster at 1km resolution containing cells where the estimated population in 2015 in HTR cells was at least 30 people using the “Raster calculator” function in QGIS 3.18.2 Zürich.12
3. We created a vector point layer from the raster in step 2 above using the “Raster pixels to points” function in QGIS 3.18.2 Zürich.12 The resulting vector point layer contained point features at the centroid of every cell at 1km resolution where the estimated population in 2015 in HTR areas was at least 30 people, resulting in 4870 candidate sites for the hypothetical CHW network in HTR areas.

See the section below on the efficiency analysis for further details on how the number of CHWs per candidate site within the hypothetical networks was calculated.

DEM
We obtained a Tagged Information File Format (GeoTiff) raster of a digital elevation model (DEM) – the NASA Shuttle Radar Topography Mission Global 1 arc second (SRTMGL1) dataset version 3.0, with a resolution of approximately 30 meters (m) x 30m (0.000277778 decimal degrees) for the area including Sierra Leone.1 The SRTMGL1 was retrieved 7 February 2021 from the online EarthExplorer, courtesy of the NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota, https://earthexplorer.usgs.gov/. More information on the SRTMGL1 is available at https://lpdaac.usgs.gov/node/527. For our analysis at 100m x 100m resolution (geographic accessibility analysis) we prepared a DEM raster at 100m x 100m resolution using the GDAL “warp” tool in QGIS 3.18.2 Zürich12 to reproject the CRS of the original file from EPSG:4326, WGS 84 to the CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N, resample the resolution to 100m x 100m using bilinear as the resampling method and clip the file to the extent of the administrative level 3 (adm3) shapefile (see GeoTIFF file “r_SLE_dem_final_100m” in Supplementary Appendix 3). For our analysis at 1km x 1km resolution (geographic coverage, efficiency, and scale-up analysis) we prepared a GeoTIFF DEM raster at 1km x 1km resolution using the GDAL “warp” tool in QGIS 3.18.2 Zürich12 and the process described above (see the GeoTIFF file “raster_dem_dem” in Supplementary Appendix 1c at https://doi.org/10.5281/zenodo.6496617).

Land cover
We obtained a GeoTIFF raster for land cover in Africa [c_gls_LC100-LCCS_201501010000_AFRRI_PROBAV_1.0.1] at a resolution of approximately 100m x 100m from the Copernicus Global Land Service,7 accessed on 27 March 2018 at https://land.copernicus.eu/global/products/lc. The land cover dataset contains discreet land cover classes based on the UN Land Cover Classification System (LCCS). Further details on the Copernicus land cover data set are available at https://land.copernicus.eu/global/products/lc. For our analysis at 100m x 100m resolution (geographic accessibility analysis) we prepared a GeoTIFF land cover raster (see the GeoTIFF file “r_SLE_land_final_100m.tif” in Supplementary Appendix 3) using the GDAL “warp” tool in
QGIS 3.18.2 Zürich\textsuperscript{12} to reproject the CRS from EPSG:4326 - WGS84 to CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N, resample the resolution to 100m x 100m using nearest neighbour as the sampling method and clip the file to the extent of the final DEM. We obtained a raster of built-up areas from the Center for International Earth Science Information Network (CIESIN), Columbia University and Novel-T, accessed on 20 June 2021 at https://data.grid3.org/datasets/GRID3::grid3-sierra-leone-settlement- extents-version-01/about to adjust cells in the land cover raster to derived from Copernicus to “urban” where the GRID3 dataset indicated the cells were “built-up areas” (see file “Comparison of Copernicus urban, GRID3 BUA and GRID3 SSA”). We manually adjusted cells in the land cover layer classes “permanent water bodies” and “herbaceous wetland” based on visual inspection using satellite imagery. For our analysis at 1km x 1km resolution (geographic coverage, efficiency, and scale-up analysis) we repeated the above within our Accessmod 5.6.56\textsuperscript{8} and the process described above. Based on visual inspection using satellite imagery we noticed that the resampling method “mode” adequately accounted for herbaceous wetland at 1km resolution but not permanent water bodies. We created a dummy raster at 100m resolution for permanent water bodies and resampled the dummy to 1km resolution using max as the resampling method. We used the GDAL “merge” function in QGIS 3.18.2 Zürich\textsuperscript{12} to merge the land cover at 1km resolution with the dummy permanent water body layer at 1km resolution, and then reclassified the “permanent water body” class values from 1 to 80 see file “r_SLE_land_final_1km.tif” in Supplementary Appendix 1c at https://doi.org/10.5281/zenodo.6496617).

**Roads**

We obtained a vector line shapefile for the road network in Sierra Leone developed by the Humanitarian OpenStreetMap Team, accessed on 27 March 2018, at https://data.humdata.org/dataset/hotosm_sierre_leone_roads.\textsuperscript{3} To prepare the final roads file, we changed the column “Highway” to “label”; reclassified the road types using the standard OpenStreetMap categories described at https://wiki.openstreetmap.org/wiki/Key:highway; simplified the road typology by excluding road types with very few segments or of little importance/relevance to the study; added a “class” variable in order to enable linking with the travel time scenarios; and reprojected the CRS from EPSG:4326 - WGS84 to CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N in alignment with the final DEM using the GDAL “warp” function in QGIS 3.18.2 Zürich\textsuperscript{12} (see file v_SLE_v1_roads_100m.shp in Supplementary Appendix 1c at https://doi.org/10.5281/zenodo.6496617). As described below in the section on the merged land cover raster, for our analysis at 100m x 100m resolution we uploaded the vector line shapefile for the road network into our Accessmod 5.6.56\textsuperscript{8} project at 100m x 100m resolution and used the merge land cover tool in Accessmod 5.6.56\textsuperscript{8} to rasterise the vector line shapefile for the road network as part of the merged land cover raster at 100m x 100m resolution. For our analysis at 1km x 1km resolution (geographic coverage, efficiency, and scale-up analysis) we repeated the above within our Accessmod 5.6.56\textsuperscript{8} project at 1km x 1km resolution.

**Rivers and Other Waterbodies**

Rivers and other waterbodies were considered barriers to movement, where they were not crossed by a road. We obtained vector line shapefiles for rivers from HOT Open Street Map (HOTOSM), accessed on 27 March 2018, at https://data.humdata.org/dataset/hotosm_sierre_leone_waterways.\textsuperscript{4} For our analysis at 100m x100m resolution (geographic accessibility), we reprojected the CRS from EPSG:4326 - WGS84 to CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N in alignment with the final DEM using the GDAL “warp” function in QGIS 3.18.2 Zürich\textsuperscript{12} (see file “v_SLE_v1_rivers_main_100m.shp” and “v_SLE_v1_rivers_major_100m.shp” in Supplementary Appendix 1c at https://doi.org/10.5281/zenodo.6496617). As described below in the section on the merged land cover raster, for our analysis at 100m x 100m resolution we uploaded the vector line file for rivers into our Accessmod 5.6.56\textsuperscript{8} project at 100m x 100m resolution and used the merge land cover tool in Accessmod 5.6.56\textsuperscript{8} to rasterise the vector line shapefile for rivers as part of the merged land cover raster at 100m x 100m resolution. For our analysis at 1km x 1km resolution (geographic coverage, efficiency, and scale-up analysis) we repeated the above within our Accessmod 5.6.56\textsuperscript{8} project at 1km x 1km resolution. We adjusted the river network layers at 100m and 1km resolution based on visual inspection of satellite imagery. Data on other water bodies (permanent and temporary) were already included as part of the land cover raster described above.

**Merged land cover**
For our geographic accessibility analysis, we prepared a merged land cover raster at 100m x 100m resolution using the “Merge land cover” tool in Accessmod 5.6.56 (see file “raster_land_cover_merged_r_SLE_land_merged_final_100m.tif” in Supplementary Appendix 1c at https://doi.org/10.5281/zenodo.6496617). The process is described in detail in Ray et al, 2008. In brief, the “Merge land cover” tool stacks, orders, and merges the road network, barriers (rivers and other waterbodies, the later from the land cover), and land cover files into a single raster dataset. For our analysis at 1km x 1km resolution (geographic coverage, efficiency, and scale-up analysis) we prepared a merged land cover raster at 1km x 1km resolution using the process described above within our Accessmod 5.6.56 project at 1km x 1km resolution (see the file “raster_occuption_du_sol_fusionnee_r_SLE_land_merged_1km.tif”).

Travel scenario tables

We developed travel scenario tables for the following scenarios walking in dry conditions, walking in wet conditions, walking to the nearest road and then using motorised transportation in dry conditions, and walking to the nearest road and then using motorised transportation in wet conditions (see files “t_SLE_walk_dry.xls”, “t_SLE_walk_wet.xls”, “t_SLE_walk_veh_dry.xls” and “t_SLE_walk_veh_wet.xls” in Supplementary Appendix 1c at https://doi.org/10.5281/zenodo.6496617). We set traveling speeds by mode of transportation (walking or walking + motorised transportation) for each land cover class and road class. Travel speeds were adapted from previous studies. Travel speeds refer to the population going to the CHW.

Population

Data preparation of population raster layers for the year 2015

We obtained a GeoTiff raster for the estimated population count for Sierra Leone in 2015 adjusted to disaggregated 2015 population census data at roughly 100m x 100m resolution, the 2015 Worldpop SLE v2.0, from https://wopr.worldpop.org/?SLE/, courtesy of Worldpop and Statistics Sierra Leone, accessed 12 July 2021. The 2015 Worldpop layer v2.0 was developed following the Random Forest (RF) – based dasymetric mapping approach and building footprints and adjusted to 2015 disaggregated census data. Details are provided at the link above.

1. We reprojected the original 2015 Worldpop GeoTiff raster file for the population count in 2015 at approximately 100m resolution from the CRS EPSG:4326 - WGS84 to the CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N in alignment with the final DEM using the GDAL “warp” function in QGIS 3.18.2 Zürich and aggregated the reprojected raster to 100 meter resolution using the r.resamp.stats GRASS 7.8.2 plugin in QGIS 3.18.2 Zürich with sum as the aggregation method and the final DEM at 100 meter resolution as the extent, resulting in the file [SLE_population_v2_0_gridded_reprojected_unadjusted].
2. We used the “Zonal statistics” tool in QGIS 3.18.2 Zürich to calculate the count of the population from the original World pop population layer in 2015 to a vector file for administrative level 3 in CRS WGS84 and used a spatial join to copy the population counts to the vector file for administrative level 3 in CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N [v_SLE_adm3_100m].
3. We used the “Zonal statistics” tool in QGIS 3.18.2 Zürich to calculate the count of the population from the raster of the 2015 population at 100 meters [SLE_population_v2_0_gridded_reprojected_unadjusted] from step 1 to the vector file [v_SLE_adm3_100m].
4. We created a ratio called “Rat15OtN” in the adm3 vector file [v_SLE_adm3_100m] that divided the population count at administrative level 3 from the original World pop population layer in 2015 from step 2 by the population count at administrative level 3 from the reprojected population layer in 2015 from step 1.
5. We rasterised this ratio at 100m resolution using the “Rasterise” tool in QGIS 3.18.2 Zürich with the ratio from step 4 as the burn and the extent of the DEM at 100m resolution as the extent. Using raster calculator in QGIS 3.18.2 Zürich, we multiplied the rasterised ratio by the Worldpop population in 2015 at 100m x 100m resolution to create a GeoTiff raster for the population in the year 2015 [r_SLE_pop15_100m_undadjusted_barriers].
6. We uploaded the file [r_SLE_pop15_100m_undadjusted_barriers] into Accessmod 5.6.56 and redistributed the population on cells with barriers to cells without barriers within the same administrative level 3 boundaries, resulting in the final raster file for the population in the year 2015 [raster_population_r_SLE_pop15_final_100m].

We repeated the steps above at 1km x 1km resolution to produce the GeoTiff raster of the population in 2015 at 1km x 1km resolution [raster_population_r_SLE_pop15F_1km] (see Supplementary Appendix 1c at https://doi.org/10.5281/zenodo.6496617).

Data preparation of population raster layers in ETR areas and HTR areas for the year 2015

1. We created a new raster layer for the population in ETR areas in 2015 at 1km x 1km resolution [raster_population_r_SLE_pop15F_ETR_1km] by multiplying the raster for the estimated population in 2015 by the dummy raster for ETR areas using the “Raster calculator” function in QGIS 3.18.2 Zürich.12

2. We created a new raster layer for the population in HTR areas in 2015 at 1km x 1km resolution [raster_population_r_SLE_pop15F_HTR_1km] by multiplying the raster for the estimated population in 2015 by the dummy raster for HTR areas using the “Raster calculator” function in QGIS 3.18.2 Zürich.12 See Supplementary Appendix 1c at https://doi.org/10.5281/zenodo.6496617.

Data preparation of population raster layers for the years 2000-2012

We obtained GeoTiff rasters for the estimated population count – unconstrained by settlement extents – for the years 2000-2014 in Sierra Leone, adjusted to UN population estimates, at roughly 100m x 100m resolution in Geographic Coordinate system WGS84 from Worldpop, accessed 5 June 2021.25 We prepared a GeoTiff raster layer for the population count in the year 2000 at 100m x 100m resolution that matched the population count from the original Worldpop GeoTiff raster layer in 2000 [sle_ppp_2000_UNadj] at the lowest administrative level (adm3) but maintained the population settlement footprint of the 2015 Worldpop SLE v.2.0. This assumes the actual population settlement footprint in 2000 would be similar to the 2015 Worldpop SEL v.20, a limitation we acknowledge in the section on limitations. We used the following steps to prepare the raster layer for the population count in 2000 at 100m x 100m resolution:

1. We reprojected the original Worldpop GeoTiff raster layer for the population in 2000 at approximately 90m x 90m resolution [sle_ppp_2000_UNadj] from the CRS EPSG:4326 - WGS84 to the CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N using the GDAL Warp tool in QGIS 3.18.2 Zürich12 and aggregated the reprojected raster to 100m x 100m meter resolution using the r.resamp.stats GRASS 7.8.2 plugin in QGIS 3.18.2 Zürich12 with sum as the aggregation method and the final DEM at 100m x 100m resolution as the extent, and then multiplied this raster by a dummy raster representing the footprint of the 2015 Worldpop SEL v.2.0, resulting in a reprojected raster for the population count in 2000 constrained to the footprint of the 2015 Worldpop SEL v.2.0. [sle_ppp_2000_UNadj_reprojected_100m], effectively

2. We used the “Zonal statistics” tool in QGIS 3.18.2 Zürich12 to calculate the count of the population from the original World pop population layer in 2000 [sle_ppp_2000_UNadj] to a vector file for administrative level 3 in CRS WGS84 and used a spatial join to copy the population counts to the vector file for administrative level 3 in CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N [v_SLE_adm3_100m].

3. We created a ratio called “Pop00OtN” in the adm3 vector file [v_SLE_adm3_100m] that divided the count from the original Worldpop population layer for 2000 from step 2 [sle_ppp_2000_UNadj] by the population count from the reprojected population layer for 2000 [raster_population_r_SLE_pop15_final_100m], which as described above, maintains the population settlement footprint of the 2015 Worldpop SEL v.2.0.

4. We rasterised this ratio at 100m resolution using the “Rasterise” tool in QGIS 3.18.2 Zürich12 with the ratio from step 3 as the burn and the extent of the DEM at 100m x 100m resolution as the extent. Using raster calculator in QGIS 3.18.2 Zürich12 we multiplied the rasterised ratio by the 2015 population [raster_population_r_SLE_pop15_final_100m] to create a raster for the population in the year 2000 [raster_population_r_SLE_pop00_final_100m]. This approach effectively maintained the spatial distribution of the population as in 2015 while adjusting the 2015 population count downward to match the population from Worldpop for the year 2000 at the administrative level 3. Note that the 2000 population layer did not need to be adjusted for population on barriers as this was already done for the 2015 population layer.
For the years 2001-2014, we repeated the steps taken above for the year 2000 using the appropriate input population layers from Worldpop to create the rasterised ratios for each year:

2001: input file from Worldpop [sle_ppp_2001_UNadj]; rasterised ratio file [r_SLE_rat01OtN_100m]
2002: input file from Worldpop [sle_ppp_2002_UNadj]; rasterised ratio file [r_SLE_rat02OtN_100m]
2003: input file from Worldpop [sle_ppp_2003_UNadj]; rasterised ratio file [r_SLE_rat03OtN_100m]
2004: input file from Worldpop [sle_ppp_2004_UNadj]; rasterised ratio file [r_SLE_rat04OtN_100m]
2005: input file from Worldpop [sle_ppp_2005_UNadj]; rasterised ratio file [r_SLE_rat05OtN_100m]
2006: input file from Worldpop [sle_ppp_2006_UNadj]; rasterised ratio file [r_SLE_rat06OtN_100m]
2007: input file from Worldpop [sle_ppp_2007_UNadj]; rasterised ratio file [r_SLE_rat07OtN_100m]
2008: input file from Worldpop [sle_ppp_2008_UNadj]; rasterised ratio file [r_SLE_rat08OtN_100m]
2009: input file from Worldpop [sle_ppp_2009_UNadj]; rasterised ratio file [r_SLE_rat09OtN_100m]
2010: input file from Worldpop [sle_ppp_2010_UNadj]; rasterised ratio file [r_SLE_rat10OtN_100m]
2011: input file from Worldpop [sle_ppp_2011_UNadj]; rasterised ratio file [r_SLE_rat11OtN_100m]
2012: input file from Worldpop [sle_ppp_2012_UNadj]; rasterised ratio file [r_SLE_rat12OtN_100m]
2013: input file from Worldpop [sle_ppp_2013_UNadj]; rasterised ratio file [r_SLE_rat13OtN_100m]
2014: input file from Worldpop [sle_ppp_2014_UNadj]; rasterised ratio file [r_SLE_rat14OtN_100m]

The processes resulted in the following final population layers for the years 2001-2014 at 100m x 100m resolution to be used in our analysis of the trends in geographic accessibility between 2000-2015 (see Supplementary Appendix 1c at https://doi.org/10.5281/zenodo.6496617):

2001: [raster_population_r_SLE_pop01_final_100m]
2002: [raster_population_r_SLE_pop02_final_100m]
2003: [raster_population_r_SLE_pop03_final_100m]
2004: [raster_population_r_SLE_pop04_final_100m]
2005: [raster_population_r_SLE_pop05_final_100m]
2006: [raster_population_r_SLE_pop06_final_100m]
2007: [raster_population_r_SLE_pop07_final_100m]
2008: [raster_population_r_SLE_pop08_final_100m]
2009: [raster_population_r_SLE_pop09_final_100m]
2010: [raster_population_r_SLE_pop10_final_100m]
2011: [raster_population_r_SLE_pop11_final_100m]
2012: [raster_population_r_SLE_pop12_final_100m]
2013: [raster_population_r_SLE_pop13_final_100m]
2014: [raster_population_r_SLE_pop14_final_100m]

**Data preparation of the raster of the population under one year of age for the year 2015**

Note: We used estimated count of infants (children under one year of age) in 2015 in lieu of estimated live births in 2015 in the calculation of the estimated under-five deaths layer (see below) because the latter was unconstrained to the footprint of the total population in 2015. We conducted a sensitivity analysis comparing the estimated under-five deaths using the estimated count of infants in 2015 versus the estimated live births in 2015 (file “SLE_births_pp_v2_2015” from Worldpop, available at https://www.worldpop.org/geodata/summary?id=792) in the calculation of under-five deaths and found a difference of only 277 under-five deaths at national level (26552 under-five deaths using infants in the calculation compared to 26829 under-five deaths using live births in the calculation). Given this very small difference, we used the raster layer for the count of infants in 2015 because it had the advantage of being constrained to the footprint of the estimated total population in 2015. We describe the steps used to prepare the raster of the count of infants in 2015 below.

We obtained a GeoTiff raster [SLE_population_v2_0_agesex_under1] for the estimated count of infants in 2015 for Sierra Leone, adjusted to 2015 census data and constrained to the footprint of the 2015 Worldpop SLE v.2.0, at roughly 1km x 1km resolution in Geographic Coordinate system WGS84 from Worldpop, accessed on August 8, 2021. We prepared a GeoTiff raster layer for the estimated count of children under one year of age in 2015 at 1km x 1km resolution to be used in our efficiency analysis for under-five deaths. We used the following steps:
1. Using the original raster for estimated count of children under one year of age in 2015 from Worldpop, we used Zonal Statistics in QGIS 3.18.2 Zürich to obtain the estimated count of children under one year of age in 2015 at administrative level 3 in CRS EPSG:4326 - WGS84.

2. We used a spatial join in QGIS 3.18.2 Zürich to join the variable for the estimated count of children under one year of age in 2015 from the administrative level 3 layer (CRS EPSG:4326 - WGS84) to the administrative level 3 layer in the project CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N.

3. We reprojected the original raster for estimated count of children under one year of age from Worldpop to CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N using the GDAL Warp tool in QGIS 3.18.2 Zürich, with the extent of the estimated total population raster for 2015 at 1km x 1km [raster_population_r_SLE_popU1F_1km].

4. We ran a Zonal Statistics in QGIS 3.18.2 Zürich for the reprojected raster for children under one year of age in 2015 constrained to the footprint of the reprojected raster for the estimated total population in 2015 at administrative level 3 in CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N.

5. Within the administrative level 3 in CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N we calculated a new variable called “ratU1OtN” for the ratio between the original estimate of children under one year of age in 2015 (step 2 above) to the new estimate of children under one year of age in 2015 from the reprojected layer constrained to the footprint of the raster for the estimated total population in 2015 (step 4 above).

6. We used the GDAL Rasterise (vector to raster) tool within QGIS 3.18.2 Zürich to create a raster in CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N at 1km x 1km resolution, using the variable “ratU1OtN” in the administrative level 3 layer as the burn [r_SLE_ratpopU1OtN_1km].

7. We used Raster Calculator in QGIS 3.18.2 Zürich to multiply the raster of the ratio from step 8 above by the reprojected raster for the estimated count of children under one year of age in 2015 constrained to the footprint of the raster of the estimated total population in 2015 (step 3), effectively adjusting the estimated count of children under one year of age in 2015 from step 3 to match the totals from the original estimated count of children under one year of age in 2015 at administrative level 3 (step 2) and resulting in a raster of estimated count of children under one year of age in 2015 constrained to the footprint of the estimated population in 2015 [raster_population_r_SLE_popU1F_1km]. See supplementary Appendix 1c at https://doi.org/10.5281/zenodo.6496617.

**Estimated under-five deaths**

We used the following steps to prepare the raster layer for the estimated count of under-five (0-5 years old) deaths in Sierra Leone in 2015 in ETR areas and HTR areas at 1km x 1km resolution to be used in our efficiency analysis:

1. We obtained a GeoTiff raster file [IHME_LMICS_UMS_2000_2017_Q_UNDERS_MEAN_Y2019M10D16] for modelled pixel-level estimates of the mean probability of under-five (0-5 years old) mortality (also known as the under-five mortality rate or U5MR) in EPSG:4326 - WGS84 at 2.5 arcminutes (approximately 5km x 5km) resolution developed by the Institute for Health Metrics and Evaluation (IHME), accessed on 8 October 2020, at http://ghdx.healthdata.org/lbd-data.

2. We used Raster Calculator in QGIS 3.18.2 Zürich to create a new raster equivalent to band 16 (U5MR for 2015) of the raster from step 1 in EPSG:4326 - WGS84 at approximately 5km x 5km resolution, maintaining the extent of the raster from step 1.

3. Using the GDAL Warp tool in QGIS 3.18.2 Zürich, we reprojected the raster for the U5MR in 2015 from step 1 above to CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N at 1km x 1km resolution, with nearest neighbour as the resampling method and the extent aligned to the raster for the total population in 2015 [IHME_LMICS_UMS_2000_2017_Q_UNDERS_MEAN_Y2019M10D16_2015_reprojected_1km].

4. We used Raster Calculator in QGIS 3.18.2 Zürich to multiply the raster for the U5MR in 2015 from step 2 above by the raster for estimated count of children under one year of age in 2015, resulting in a raster for the number of U5 deaths in 2015 in CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N at 1km x 1km resolution [raster_population_r_SLE_U5dF_1km]. Note: We used estimated count of infants in 2015 in lieu of estimated live births in the calculation of the estimated under-five deaths layer because the latter was unconstrained to footprint of the total population in 2015. We conducted a sensitivity analysis comparing the estimated under-five deaths using the estimated count of infants in 2015 versus the estimated live births in 2015.
We obtained a GeoTIFF raster file for modelled pixel-level estimates of the annual mean incidence of *Plasmodium falciparum* (Pf) malaria among all ages (0-99 years) in 2015 globally at 2.5 arcminutes (approximately 5km x 5km) resolution developed by the Malaria Atlas Project,\(^4\) accessed on 23 October 2020, at [https://malariaatlas.org/malaria-burden-data-download](https://malariaatlas.org/malaria-burden-data-download).

2. Using the GDAL Warp tool in QGIS 3.18.2 Zürich\(^1\), we reprojected the raster for mean incidence of Pf malaria (all ages) in 2015 to CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N at 1km x 1km resolution, using the extent of the raster for the estimated total population in 2015 as the extent [2020_GBD2019_Global_Pf_Incidence_Rate_2015_reprojected_1km].

3. We used the “Raster calculator” tool in QGIS 3.18.2 Zürich\(^1\) to prepare a GeoTIFF raster for the count of Pf malaria among all ages (0-99 years) in 2015 at 1km x 1km resolution [raster_population_r_SLE_cases_1km] by multiplying the reprojected raster for the mean incidence of Pf malaria (all ages) in 2015 from step 2 [2020_GBD2019_Global_Pf_Incidence_Rate_2015_reprojected_1km] by the raster for the estimated total population in Sierra Leone in 2015 [raster_population_r_SLE_pop15F_1km] with the CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N at 1km x 1km resolution, using the extent of the raster of the estimated population in 2015 as the extent.

4. We used the “Raster calculator” tool in QGIS 3.18.2 Zürich\(^1\) to prepare a GeoTIFF raster for the estimated count of Pf malaria cases in 2015 in ETR areas [raster_population_r_SLE_cases_ETR_1km] and HTR areas [raster_population_r_SLE_cases_HTR_1km] by multiplying the estimated count of Pf malaria cases in 2015 from step 3 above [raster_population_r_SLE_pop15F_1km] by a dummy raster for ETR areas and HTR areas (see Supplementary Appendix 1c at [https://doi.org/10.5281/zenodo.6496617](https://doi.org/10.5281/zenodo.6496617)).

Note that we did not need to adjust for the estimated Pf malaria cases on barriers because this step was conducted when preparing the raster for the estimated count of infants in 2015.

We repeated the steps above using GeoTIFF raster files for the 95% lower bound estimate for mean incidence of Pf malaria (all ages) in 2015 [incidence_rate_LCI_Global_admin0_2015] and the 95% upper bound estimate for mean incidence of Pf malaria (all ages) in 2015 [incidence_rate_UCI_Global_admin0_2015] to create GeoTIFF rasters for

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(file “SLE_births_pp_v2_2015” from Worldpop, available at [https://www.worldpop.org/geodata/summary?id=792](https://www.worldpop.org/geodata/summary?id=792)) in the calculation of under-five deaths and found a difference of only 277 under-five deaths at national level (26552 using infants compared to 26829 using live births). Given this very small difference, we used the raster layer for the count of infants in 2015 because it had the advantage of being constrained to the footprint of the estimated total population in 2015.

5. We used Raster Calculator in QGIS 3.18.2 Zürich\(^1\) to multiply the raster for the number of U5 deaths in 2015 by a dummy raster for ETR areas and HTR areas, resulting in rasters for the estimated number of U5 deaths in 2015 in ETR areas [raster_population_r_SLE_U5dF_ETR_1km] and HTR areas [raster_population_r_SLE_U5dF_HTR_1km]. See supplementary Appendix 1c at [https://doi.org/10.5281/zenodo.6496617](https://doi.org/10.5281/zenodo.6496617)).

Note that we did not need to adjust for the estimated under-five deaths on barriers because this step was conducted when preparing the raster for the estimated count of infants in 2015.

We repeated the steps above using GeoTIFF raster files for the 95% lower bound estimate for U5 mortality rate [IHME_LMICS_U5M_2000_2017_Q_UNDER5_LOWER_Y2019M10D16] and the 95% upper bound estimate for U5 mortality rate [IHME_LMICS_U5M_2000_2017_Q_UNDER5_UPPER_Y2019M10D16] to create GeoTIFF rasters for estimated lower bound number of U5 deaths in 2015 [raster_population_r_SLE_U5dF_LCI_1km] and estimated upper bound U5 deaths in 2015 [raster_population_r_SLE_U5dF_UCI_1km].

Estimated *Plasmodium falciparum* malaria cases

We used the following steps to prepare a GeoTIFF raster layer for the estimated count of *Plasmodium falciparum* malaria cases among all ages (0-99 years) in Sierra Leone in 2015 at 1km x 1km resolution to be used in our efficiency analysis:

1. We obtained a GeoTIFF raster file for modelled pixel-level estimates of the annual mean incidence of *Plasmodium falciparum* (Pf) malaria among all ages (0-99 years) in 2015 globally at 2.5 arcminutes (approximately 5km x 5km) resolution developed by the Malaria Atlas Project,\(^4\) accessed on 23 October 2020, at [https://malariaatlas.org/malaria-burden-data-download](https://malariaatlas.org/malaria-burden-data-download).

2. Using the GDAL Warp tool in QGIS 3.18.2 Zürich\(^1\), we reprojected the raster for mean incidence of Pf malaria (all ages) in 2015 to CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N at 1km x 1km resolution, using the extent of the raster for the estimated total population in 2015 as the extent [2020_GBD2019_Global_Pf_Incidence_Rate_2015_reprojected_1km].

3. We used the “Raster calculator” tool in QGIS 3.18.2 Zürich\(^1\) to prepare a GeoTIFF raster for the count of Pf malaria among all ages (0-99 years) in 2015 at 1km x 1km resolution [raster_population_r_SLE_cases_1km] by multiplying the reprojected raster for the mean incidence of Pf malaria (all ages) in 2015 from step 2 [2020_GBD2019_Global_Pf_Incidence_Rate_2015_reprojected_1km] by the raster for the estimated total population in Sierra Leone in 2015 [raster_population_r_SLE_pop15F_1km] with the CRS EPSG:2161 – Sierra Leone 1968 / UTM zone 28N at 1km x 1km resolution, using the extent of the raster of the estimated population in 2015 as the extent.

4. We used the “Raster calculator” tool in QGIS 3.18.2 Zürich\(^1\) to prepare a GeoTIFF raster for the estimated count of Pf malaria cases in 2015 in ETR areas [raster_population_r_SLE_cases_ETR_1km] and HTR areas [raster_population_r_SLE_cases_HTR_1km] by multiplying the estimated count of Pf malaria cases in 2015 from step 3 above [raster_population_r_SLE_pop15F_1km] by a dummy raster for ETR areas and HTR areas (see Supplementary Appendix 1c at [https://doi.org/10.5281/zenodo.6496617](https://doi.org/10.5281/zenodo.6496617)).

Note that we did not need to adjust for the estimated Pf malaria cases on barriers because this step was conducted when preparing the raster for the estimated population in 2015.
estimated lower bound number of *Pf* malaria cases (all ages) in 2015 [raster_population_r_SLE_cases_LCI_1km] and estimated upper bound *Pf* malaria cases (all ages) in 2015 [raster_population_r_SLE_cases_UCI_1km].

**Analysis**

**Assessing accessibility coverage**

Research questions

1. What was geographic accessibility to the health facility network in 2015?
   a. What percentage of the population was within 10 min, 30 min and 60 min of a health facility in 2015, assuming a walking scenario in dry conditions? How did this vary across geographies?
   b. Same as (a) above for walking in wet conditions, walking to the nearest road and then using motorised transportation in dry conditions, walking to the nearest road, and then using motorised transportation in wet conditions. How did this vary across geographies?

2. What was geographic accessibility to the CHW network in 2015?
   a. What percentage of the population was within 10 min, 30 min and 60 min of a CHW in 2015, assuming a walking scenario in dry conditions? How did this evolve over time 2000-2015? What was accessibility coverage of CHW in ETR areas and HTR areas?
   b. Same as (a) above for walking in wet conditions, walking to the nearest road and then using motorised transportation in dry conditions, walking to the nearest road, and then using motorised transportation in wet conditions.
   c. Same as (a) above by CHW gender, pre-service training, and training on specific interventions

**Methods for accessibility coverage research question 1**

We define accessibility coverage as the estimated percentage of people within a given travel time to the nearest health service delivery location of a given health service delivery network, accounting for travel speeds of different modes of transportation over different land cover classes and slope, with the direction of travel toward the health service delivery location. We estimated accessibility coverage at 100m x 100m resolution for the health facility and CHW networks in 2015 – and for the CHW network by gender, year of deployment (2000-2015), pre-service training and training on specific interventions – using 10-minute, 30-minute and 60-minute cut-offs for administrative levels 0-3 and the four travel scenarios. We used 10-minute, 30-minute and 60-minute cut-offs as previous analyses have shown careseeking decays as a function of travel time after these cutoffs and they are clinically relevant (e.g., for prompt treatment of severe illness). The analysis was constrained to national borders but allowed for travel across subnational administrative boundaries. We used the “geographic accessibility” module within Accessmod 5.6.56 to calculate travel time layers and the “zonal statistics” module to calculate the zonal statistics for each travel time layer by administrative level. For our analysis of accessibility coverage in 2015, we used the CHW network from 2016 (data collected up to March 2016).

Analysis

1. We conducted a geographic accessibility analysis of the existing health facility network in 2015 based on a travel scenario of walking in dry conditions scenario at 100m x 100m resolution using Accessmod 5.6.56.
   a. We used the following data inputs:
      i. Population: raster_population_r_SLE_pop15F_1km
      ii. Land cover merged: raster_occupation_du_sol_fusionnee_r_SLE_land_merged_1km
      iii. Scenario table: table_scenario_walk_dry
      iv. Select existing health facilities layer (vector): v_SLE_facilities_final_1km
      v. ID field: uid
      vi. Facility name field: name
      vii. Select zones layer (vector): adm3
         1. Select zones unique ID (integer): objectid
         2. Select zone name (text): name_3
   b. We used the following analysis settings:
i. Type of analysis: anisotropic
ii. Direction of travel: towards facilities
iii. Maximum travel time (minutes): 0
iv. Options
  1. Optimise dynamically computation according to the scenario: Yes
  2. Add short tag: raster_travel_time_r_SLE Ga_facilities_wd_100m

2. We repeated steps 1 using a travel scenario for following scenarios:
   a. walking in wet conditions: raster_travel_time_r_SLE Ga_facilities_ww_100m
   b. walking to the nearest road, then using motorised transportation in dry conditions:
      raster_travel_time_r_SLE Ga_facilities_wd_100m
   c. walking to the nearest road, then using motorised transportation in dry conditions:
      raster_travel_time_r_SLE Ga_facilities_wvd_100m

3. We used the “Zonal statistics” tool within Accessmod 5.6.56 to calculate the percent of the population within 10 minutes, 30 minutes, and 60 minutes travel time in 2015 for each travel scenario (see Table 1 and Supplementary Appendix 2).

Methods for accessibility coverage research question 2

We repeated the analysis described in Methods for Geographic Accessibility question 1, using the relevant CHW vector point layer (gender, year of deployment, pre-service training, training on specific interventions) and travel scenario. For accessibility coverage in ETR areas and HTR areas, we used the rasters for the estimated population in ETR areas and HTR areas in 2015 as population inputs, otherwise the raster for the estimated population in 2015 was used for all analyses.

See Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.6496617. See Table 1 for zonal statistics from these travel time rasters and detailed results for administrative layers 0-3 in Supplementary Appendix 2.

Assessing efficiency

We assessed efficiency of the existing network of CHW in 2016 in terms of geographic coverage of a) the estimated population in ETR areas and HTR areas in 2015 b) the estimated under-five deaths in ETR areas and HTR areas in 2015 and c) the estimated Pf malaria cases in ETR areas and HTR areas in 2015 compared to hypothetical CHW networks in ETR areas and HTR areas in 2016.

Hypothetical networks in ETR areas:

a. Hypothetical CHW network that optimised geographic coverage of the estimated population in ETR areas in 2015 by ordering the deployment (processing order) based on the estimated population in ETR areas 2015 within the catchment area of a given CHW, prioritising catchments with higher estimated population in ETR areas over those with lower estimated population in ETR areas.

b. Hypothetical CHW network that optimised geographic coverage of the estimated under-five deaths in ETR areas in 2015 by ordering the deployment (processing order) based on the estimated under-five deaths in ETR areas in 2015 within the catchment area of a given CHW, prioritising catchments with higher estimated under-five deaths in ETR areas over those with lower estimated under-five deaths in ETR areas.

c. Hypothetical CHW network that optimised geographic coverage of the estimated Pf malaria cases among all ages (0-99 years) in ETR areas in 2015 by ordering the deployment (processing order) based on the estimated Pf malaria cases among all ages (0-99 years) in 2015 within the catchment area of a given CHW, prioritising catchments with higher estimated Pf malaria cases in ETR areas over those with lower estimated Pf malaria cases in ETR areas.

Hypothetical networks in HTR areas:
a. Hypothetical CHW network that optimised geographic coverage of the estimated population in ETR areas in 2015 by ordering the deployment (processing order) based on the estimated population in ETR areas 2015 within the catchment area of a given CHW, prioritising catchments with higher estimated population in ETR areas over those with lower estimated population in ETR areas.

b. Hypothetical CHW network that optimised geographic coverage of the estimated under-five deaths in ETR areas in 2015 by ordering the deployment (processing order) based on the estimated under-five deaths in ETR areas in 2015 within the catchment area of a given CHW, prioritising catchments with higher estimated under-five deaths in ETR areas over those with lower estimated under-five deaths in ETR areas.

c. Hypothetical CHW network that optimised geographic coverage of the estimated Pf malaria cases among all ages (0-99 years) in ETR areas in 2015 by ordering the deployment (processing order) based on the estimated Pf malaria cases among all ages (0-99 years) in 2015 within the catchment area of a given CHW, prioritising catchments with higher estimated Pf malaria cases in ETR areas over those with lower estimated Pf malaria cases in ETR areas.

We defined geographic coverage as the theoretical catchment area of a health service delivery location, within a maximum travel time, accounting for the mode of transportation and the maximum population capacity of the type of health service delivery location.9 We used the “geographic coverage” module of AccessMod 5.6.56 to estimate geographic coverage of the estimated population in ETR areas and HTR areas by the CHW network in 2015 at 1km x 1km resolution for the walking in dry conditions travel scenario. The maximum travel time was set at 30 minutes for CHWs. The maximum population capacity for CHWs was based on MOHS norms for the ratio of CHWs per population from the 2021 CHW policy18 – with the aim of informing operationalization of the 2021 CHW strategy and future fine-tuning (e.g. to inform decisions that optimise deployment of new CHW to replace CHWs that leave service through attrition). We used the lower bound of the MOHS range for the CHW per population ratios in ETR areas and HTR areas to be conservative in our estimates: 500 for CHWs in ETR areas and 300 for CHWs in HTR areas. The maximum extent of a catchment was therefore delimited by the maximum travel time of 30 minutes except in cases where the estimated population in the catchment exceeded the maximum population capacity of the CHW – in which case the extent of the catchment was smaller than the maximum travel time and was defined by the area containing the estimated population, up to the maximum population capacity.

Because we did not know the actual order of scale-up of the existing CHW network (we only have year of deployment of each CHW and are unable to distinguish order of deployment within each year) and because we wanted to ensure a conservative estimate efficiency, for the comparison of geographic coverage of the population in ETR areas and HTR areas we assumed the prioritization order for the existing CHW networks in ETR areas and HTR areas based on the estimated population in ETR areas and HTR areas within a 30-minute catchment (walking) of an existing CHW (as with the hypothetical networks in (a) above). For comparison of geographic coverage of the estimated U5 deaths in ETR areas and HTR areas we assumed the prioritization order for the existing CHW network based on the estimated U5 deaths in ETR areas and HTR areas within a 30-minute catchment (walking) of an existing CHW (as with the hypothetical networks in (b) above). For comparison of geographic coverage of the estimated Pf malaria cases in ETR areas and HTR areas we assumed the prioritization order for the existing CHW network based on the estimated Pf malaria cases in ETR areas and HTR areas within a 30-minute catchment (walking) of an existing CHW (as with the hypothetical networks in (c) above). This is likely to overestimate the slope (efficiency) for the existing network and result in a conservative (underestimated) estimate of the gains in efficiency of the hypothetical network over the existing network. This conservative approach to estimating efficiency gains of the hypothetical network over the existing network is justified given the absence of knowledge of the true criteria and/or factors that determined the scale-up order of the existing CHW network.

Research questions

1. How well targeted was the existing network of CHW in 2016 in ETR areas and HTR areas in terms of geographic coverage of the estimated population in ETR areas and HTR areas in 2015 compared to hypothetical networks of CHW in ETR areas and HTR areas deployed to optimise geographic coverage of the estimated...
population in ETR areas and HTR areas in 2015? See Supplementary Appendix 3, tabs “Comparison_Pop_ETR” and “Comparison_Pop_HTR” for results.

2. How well targeted was the existing network of CHW in 2016 in ETR areas and HTR areas in terms of geographic coverage of the estimated under-five deaths in ETR areas and HTR areas in 2015 compared to hypothetical networks of CHW in ETR areas and HTR areas deployed to optimise geographic coverage of the estimated under-five deaths in ETR areas and HTR areas in 2015? See Supplementary Appendix 3, tabs “Comparison_U5d_ETR” and “Comparison_U5d_HTR” for results.

3. How well targeted was the existing network of CHW in 2016 in ETR areas and HTR areas in terms of geographic coverage of the estimated *Pf* malaria cases among all ages (0-99 years) in ETR areas and HTR areas in 2015 compared to hypothetical networks of CHW in ETR areas and HTR areas deployed to optimise geographic coverage of the estimated *Pf* malaria cases among all ages (0-99 years) in ETR areas and HTR areas in 2015? See Supplementary Appendix 3, tabs “Comparison_Cases_ETR” and “Comparison_Cases_HTR” for results.

See Supplementary Appendix 1b at [https://doi.org/10.5281/zenodo.6496617](https://doi.org/10.5281/zenodo.6496617) for the vector shapefile (polygons) of the modelled catchment area of the existing CHW networks in ETR areas and HTR areas in 2015.

**Methods for efficiency research question 1**

**Data preparation**

1. See Methods section “Data preparation of population raster layers in ETR areas and HTR areas for the year 2015” for details on preparation of the estimated population layer for ETR in 2015
   [raster_population_r_SLE_pop15F_ETR_1km] and HTR areas in 2015
   [raster_population_r_SLE_pop15F_HTR_1km]

**Data analysis**

1. Geographic coverage analysis of the estimated population in ETR areas by the existing network of CHW, prioritising estimated residual population: See Methods for Geographic Coverage research question 2, Data analysis, step 1.

2. Geographic coverage analysis of the estimated population in ETR areas by the existing network of CHW, prioritising estimated population in ETR areas: We conducted a geographic coverage analysis for the existing network of CHW in ETR areas (n=1521) in 2016 at 1 km x 1 km resolution for the walking in dry conditions. We set the maximum travel time to 30 minutes. We set the maximum population capacity for CHWs in ETR areas at 500 based on MOHS norms for ETR areas. We used a descending processing order (highest to lowest) based on the estimated population in ETR areas in 2015 within each 30-minute catchment area. This prioritised the deployment of the existing CHW in ETR areas according to the size (highest to lowest) of the estimated population in ETR areas within each 30-minute catchment. This provided the final outputs for the geographic coverage analysis for the existing network of CHW in ETR areas that prioritised geographic coverage of the estimated population in ETR areas.
   a. We used the following data inputs:
      i. Population: raster_population_r_SLE_pop15F_ETR_1km
      ii. Land cover merged: raster_occupation_du_sol_fusionnee_r_SLE_land_merged_1km
      iii. Scenario table: table_scenario_walk_dry
      iv. Select existing health facilities layer (vector): v_SLE_Existing_CHW_ETR_1km
      v. ID field: id
      vi. Facility name field: cat
      vii. Capacity: capacity
      viii. Select zones layer (vector): adm3
         1. Select zones unique ID (integer): objectid
         2. Select zone name (text): nom_com
   b. We used the following analysis settings:
      i. Type of analysis: anisotropic
ii. Direction of travel: towards facilities

iii. Facilities processing order according to: The population living within a given travel time from the facilities
   1. Travel time (minutes) for prioritization: 30

iv. Processing order: Descending

v. Maximum travel time (minutes): 30

vi. Options
   1. Compute population catchment area layer: Yes
   2. Remove the covered population at each iteration: Yes
   3. Compute a layer of population cells on barriers: Yes
   4. Generate zonal statistics: Yes (adm 3)
   5. Run the analysis without considering capacities: No
   6. Add column with original population sum under each facility’s travel time: Yes
   7. Optimise dynamically computation according to the scenario: Yes
   8. Add short tag: r_SLE_gc_Existing_CHW_ETR_30min_prioritisePop30min_wd_1km

We repeated the above for the existing network in HTR areas, the hypothetical network in ETR areas and the hypothetical network in HTR areas. The parameters were the same as above, except for the population (the estimated population in HTR areas was used for HTR scenarios), the CHW network (the relevant CHW network was used) and the maximum population capacity (500 for CHW in ETR areas and 300 for CHW in HTR areas based on MOHS norms).

For outputs, see Supplementary Appendix 3, tabs “Existing_Pop_ETR”, “Existing_Pop_HTR”, “Hypo_Pop_ETR” and “Hypo_Pop_HTR”, in which the variable “amPopCoveredPercent” indicates the cumulative geographic coverage of the estimated population in the given area (ETR or HTR). Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.6496617 contains the vector shapefile (polygon) indicating the modelled catchment area of each health service delivery point.

3. In tab “Comparison_Pop_ETR” of Supplementary Appendix 3, we compared the percentage of the estimated population in ETR areas in 2015 that was covered by the existing network of CHW in ETR areas in 2016 within a 30-minute catchment (walking scenario) with the same for the hypothetical network of CHW in ETR areas that prioritised the processing order based on the size (largest to smallest) of the estimated population in each catchment, given the same number of potential CHW as in the existing network of CHW in ETR areas (n=1521). The comparison is expressed as a relative difference (column D) and absolute difference (column C). Tab “Comparison_Pop_HTR” summarises the comparison between the existing CHW network in HTR areas and the hypothetical CHW network in HTR that prioritised the estimated population in HTR areas in the processing order, given the same number of potential CHW as in the existing network of CHW in HTR areas (n=3650).

Methods for efficiency research question 2

Data preparation

1. Preparation of the GeoTiff for the estimated count of residual under-five deaths beyond the geographic coverage of the existing CSI network
   a. See section I. Data inputs, Estimated under-five mortality for details.

Analysis

Geographic coverage analysis of the estimated under-five deaths in ETR areas in 2015 by the existing network of CHW in ETR areas: We conducted a geographic coverage analysis for the estimated under-five deaths in ETR areas in 2015, with the processing order based on the estimated number of U5 deaths within 30 minutes walking of the CHW and the maximum population capacity set to 100000 (variable “capacityN”) to effectively not consider maximum population capacity as a constraint to the CHW catchment areas. The analysis removed the under-five
deaths within each catchment area at each iteration (calculation of each catchment area) to avoid double counting under-five deaths where the 60 min catchment areas overlap. This provided the final outputs for the geographic coverage analysis for the existing CHW network.

a. We used the following data inputs:
   i. Population: raster_r_SLE_U5dF_ETR_1km
   ii. Land cover merged: raster_occupation_du_sol_fusionnee_r_SLE_land_merged_1km
   iii. Scenario table: table_scenario_walk_dry
   iv. Select existing health facilities layer (vector): v_Master_CHW_List_final_1km_ETR
   v. ID field: CHW_id
   vi. Facility name field: facility_c
   vii. Capacity: capacityN
   viii. Select zones layer (vector): adm3
       1. Select zones unique ID (integer): cat
       2. Select zone name (text): name_3

b. We used the following analysis settings:
   ix. Type of analysis: anisotropic
   x. Direction of travel: towards facilities
   xi. Facilities processing order according to: The population within a catchment based on travel time (30 minutes)
   xii. Processing order: Descending
   xiii. Maximum travel time (minutes): 30
   xiv. Options
       1. Compute population catchment area layer: Yes
       2. Remove the covered population at each iteration: Yes
       3. Compute a layer of population cells on barriers: Yes
       4. Generate zonal statistics: Yes (adm 3)
       5. Run the analysis without considering capacities: No
       6. Add column with original population sum under each facility’s travel time: Yes
       7. Optimise dynamically computation according to the scenario: Yes
       8. Add short tag:
           r_SLE_gc_Existing_CHW_ETR_30min_prioritiseU5d30min wd_1km

There is no MOHS norm for the ratio of CHW per U5 deaths and thereby no maximum capacity limit of the CHW for U5 deaths. Rather than make the unrealistic assumption that one CHW could cover all U5 deaths within their catchment regardless of population size, we calculated the number of CHW required in both the existing CHW network in ETR areas and the hypothetical CHW network in ETR areas to completely cover (saturate) the estimated population in each catchment based on the MOHS norm of one CHW per 500 population in ETR areas.

We repeated the above for the existing network in HTR areas, the hypothetical network in ETR areas and the hypothetical network in HTR areas. The parameters were the same as above, except for the population (the estimated U5 deaths in HTR areas was used for HTR scenarios), and the CHW network (the relevant CHW network was used). The maximum population capacity was set to 500 for ETR areas and 300 in HTR areas per MOHS norms for the ratio of CHW per population.

For outputs, see Supplementary Appendix 3, tabs “Existing_U5d_ETR”, “Existing_U5d_HTR”, “Hypo_U5d_ETR” and “Hypo_U5d_HTR”, in which the variable “amPopCoveredPercent” indicates the cumulative geographic coverage of the estimated U5 deaths in the given area (ETR or HTR). Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.6496617 contains the vector shapefile (polygon) indicating the modelled catchment area of each health service delivery point.

2. In tab “Comparison_U5d_ETR” of Supplementary Appendix 3, we compared the percentage of the estimated U5 deaths in ETR areas in 2015 that was covered by the existing network of CHW in ETR areas in 2016 within a 30-minute catchment (walking scenario) with the same for the hypothetical network of CHW in ETR areas
that prioritised the processing order based on the size (largest to smallest) of the estimated number of U5 deaths in each catchment, given the same number of potential CHW as in the existing network of CHW in ETR areas (n= 1521). The comparison is expressed as a relative difference (column D) and absolute difference (column C). Tab “Comparison_U5d_ETR” summarises the comparison between the existing CHW network in ETR areas and the hypothetical CHW network in HTR that prioritised the processing order based on the size (largest to smallest) of the estimated number of U5 deaths in each catchment, given the same number of potential CHW as in the existing network of CHW in HTR areas (n= 3650).

Uncertainty analysis

We assessed the potential effect of uncertainty of the estimates for U5 deaths on efficiency as follows. We used the “Zonal statistics” tool in QGIS 3.12.0-București to extract the estimated mean and 95% confidence intervals for the number of U5 deaths in 2015 for each catchment area defined by the geographic coverage analysis from step 1 of efficiency research question 2. We sorted the catchments by the estimated mean number of under-five deaths in 2015 from largest to smallest, as this reflected the prioritization order of the geographic coverage analysis used for the efficiency analysis (step 2 of efficiency research question 2). Because policy makers and planners typically support scale-up of CHWs in groups we divided each network into groups of ~250 CHWs for consideration. For U5 deaths in ETR areas with the existing CHW network, this resulted in 6 groups with 250 CHW each (see tab “Summary_U5d15_ETR_exist”). Group 1 included the 250 CHW with the highest estimated mean number of under-five deaths in 2015, (median of means across catchments = 5.4, median of lower 95% confidence interval = 4.7, and median of upper 95% confidence interval = 6.2). Group 2 included the 250 CHW with the next highest estimated mean number of under-five deaths (median of means across catchments = 2.8, median of lower 95% confidence interval = 2.4, and upper 95% confidence interval = 3.2). Group 3 included the 250 CHW with next highest estimated mean number of under-five deaths (median of means across catchments = 1.6, median of lower 95% confidence interval = 1.4, and median of upper 95% confidence interval = 1.9). Group 4 included the 250 CHW with the next highest mean number of under-five deaths (median of means across catchments = 0.9, median of lower 95% confidence interval minimum = 0.8, and median of upper 95% confidence interval = 1.0). Group 5 included the 250 CHW with the next highest estimated mean number of under-five deaths (median of means across catchments = 0.4, median of lower 95% confidence interval = 0.4, median of upper 95% confidence interval = 0.5). Group 6 included the 271 CHW with the next highest estimated mean number of under-five deaths (median of means across catchments = 0.1, median of lower 95% confidence interval = 0.1, median of upper 95% confidence interval = 0.1). Based on the medians of the 95% confidence intervals, decision makers could confidently prioritise Group 1 over Groups 2-6; Group 2 over Groups 3-6; Group 3 over Groups 4-6; Group 4 over Groups 5-6, and Group 5 over Group 6 (see Supplementary Appendix 4, tab “Summary_U5d15_ETR_exist”). The same analysis was done for U5 deaths in HTR areas for the existing network of CHWs (see Supplementary Appendix 4, tab “Summary_U5d15_HTR_exist”), U5 deaths in ETR areas for the hypothetical network (see Supplementary Appendix 4, tab “Summary_U5d15_ETR_hypo”), and U5 deaths in HTR areas for the hypothetical network (see Supplementary Appendix 4, tab “Summary_U5d15_HTR_hypo”).

Methods for efficiency research question 3

Data preparation

1. Preparation of the GeoTiff for the estimated count of residual Pf malaria cases among all ages (0-99 years): See section I. Data inputs, Estimated Plasmodium falciparum malaria cases

Analysis

Geographic coverage analysis of the estimated Pf malaria cases among all ages (0-99 years) in ETR areas by the existing network of CHW in ETR areas: We conducted a geographic coverage analysis for the estimated Pf malaria cases among all ages (0-99 years) in ETR areas in 2015, with the processing order based on the estimated number of Pf malaria cases among all ages (0-99 years) within 30 minutes walking of the CHW and the maximum population capacity set to 100000 (variable “capacityN”) to effectively not consider maximum population capacity as a constraint to the CHW catchment areas. The analysis removed the under-five deaths within each catchment area at...
each iteration (calculation of each catchment area) to avoid double counting under-five deaths where the 60 min catchment areas overlap. This provided the final outputs for the geographic coverage analysis for the existing CHW network.

a. We used the following data inputs:
   i. Population: raster_population_r_SLE_cases_ETR_1km
   ii. Land cover merged: raster_occupation_du_sol_fusionnee_r_SLE_land_merged_1km
   iii. Scenario table: table_scenario_walk_dry
   iv. Select existing health facilities layer (vector): v_Master_CHW_List_final_1km_ETR
   v. ID field: CHW_id
   vi. Facility name field: facility_c
   vii. Capacity: capacityN
   viii. Select zones layer (vector): adm3
        1. Select zones unique ID (integer): cat
        2. Select zone name (text): name_3

b. We used the following analysis settings:
   ix. Type of analysis: anisotropic
   x. Direction of travel: towards facilities
   xi. Facilities processing order according to: The population within a catchment based on travel time (30 minutes)
   xii. Processing order: Descending
   xiii. Maximum travel time (minutes): 30
   xiv. Options
        1. Compute population catchment area layer: Yes
        2. Remove the covered population at each iteration: Yes
        3. Compute a layer of population cells on barriers: Yes
        4. Generate zonal statistics: Yes (adm 3)
        5. Run the analysis without considering capacities: No
        6. Add column with original population sum under each facility’s travel time: Yes
        7. Optimise dynamically computation according to the scenario: Yes
        8. Add short tag:
           r_SLE_gc_Existing_CHW_ETR_30min_prioritiseCases30min_wd_1km

There is no MOHS norm for the ratio of CHW per Pf malaria cases and thereby no maximum capacity limit of the CHW for Pf malaria cases. Rather than make the unrealistic assumption that one CHW could cover all Pf malaria cases within their catchment regardless of population size, we calculated the number of CHW required in both the existing CHW network in ETR areas and the hypothetical CHW network in ETR areas to completely cover (saturate) the estimated population in each catchment based on the MOHS norm of one CHW per 500 population in ETR areas.

We repeated the above for the existing network in HTR areas, the hypothetical network in ETR areas and the hypothetical network in HTR areas. The parameters were the same as above, except for the population (the estimated U5 deaths in HTR areas was used for HTR scenarios), and the CHW network (the relevant CHW network was used). The maximum population capacity was set to 500 for ETR areas and 300 in HTR areas per MOHS norms for the ratio of CHW per population.

For outputs, see Supplementary Appendix 3, tabs “Existing_Cases_ETR”, “Existing_Cases_HTR”, “Hypo_Cases_ETR” and “Hypo_Cases_HTR”, in which the variable “amPopCoveredPercent” indicates the cumulative geographic coverage of the estimated Pf malaria cases among all ages (0-99 years) in the given area (ETR or HTR). Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.6496617 contains the vector shapefile (polygon) indicating the modelled catchment area of each health service delivery point.

2. In tab “Comparison_Cases_ETR” of Supplementary Appendix 3, we compared the percentage of the estimated Pf malaria cases among all ages (0-99 years) in ETR areas in 2015 that was covered by the existing network of
CHW in ETR areas in 2016 within a 30-minute catchment (walking scenario) with the same for the hypothetical network of CHW in ETR areas that prioritised the processing order based on the size (largest to smallest) of the estimated number of Pf malaria cases among all ages (0-99 years) in each catchment, given the same number of potential CHW as in the existing network of CHW in ETR areas (n= 1521). The comparison is expressed as a relative difference (column D) and absolute difference (column C). Tab “Comparison_Cases_HTR” summarises the comparison between the existing CHW network in HTR areas and the hypothetical CHW network in HTR that prioritised the processing order based on the size (largest to smallest) of the estimated number of Pf malaria cases among all ages (0-99 years) in each catchment, given the same number of potential CHW as in the existing network of CHW in HTR areas (n= 3650).

Uncertainty analysis

We assessed the potential effect of uncertainty of the estimates for Pf malaria cases among all ages (0-99 years) on efficiency as follows. We used the “Zonal statistics” tool in QGIS 3.12.0-Bucureşti15 to extract the estimated mean and 95% confidence intervals for the number of Pf malaria cases among all ages (0-99 years) in 2015 for each catchment area defined by the geographic coverage analysis from step 1 of efficiency research question 2. We sorted the catchments by the estimated mean number of Pf malaria cases among all ages (0-99 years) in 2015 from largest to smallest, as this reflected the prioritization order of the geographic coverage analysis used for the efficiency analysis (step 2 of efficiency research question 2). Because policy makers and planners typically support scale-up of CHWs in groups we divided each network into groups of ~250 CHWs for consideration. For Pf malaria cases among all ages (0-99 years) in ETR areas with the existing CHW network, this resulted in 6 groups with 250 CHW each (see tab “Summary_U5d15_ETR_exist”). Group 1 included the 250 CHW with the highest estimated mean number of Pf malaria cases among all ages (0-99 years) in 2015, (median of means across catchments = 648.6, median of lower 95% confidence interval = 435.4, and median of upper 95% confidence interval = 851.8). Group 2 included the 250 CHW with the next highest estimated mean number of under-five deaths (median of means across catchments = 357.7, median of lower 95% confidence interval = 252.4, and upper 95% confidence interval = 466.5). Group 3 included the 250 CHW with next highest estimated mean number of under-five deaths (median of means across catchments = 193.8, median of lower 95% confidence interval = 139.8, and median of upper 95% confidence interval = 255.5). Group 4 included the 250 CHW with the next highest mean number of under-five deaths (median of means across catchments = 110.4, median of lower 95% confidence interval minimum = 0.8, and median of upper 95% confidence interval = 143.6). Group 5 included the 250 CHW with the next highest estimated mean number of under-five deaths (median of means across catchments = 54.3, median of lower 95% confidence interval = 37.8, median of upper 95% confidence interval = 71.6). Group 6 included the 271 CHW with the next highest estimated mean number of under-five deaths (median of means across catchments = 12.2, median of lower 95% confidence interval = 8.3, median of upper 95% confidence interval = 16.2). Based on the medians of the 95% confidence intervals, decision makers could confidently prioritise Group 1 over Groups 3-6; Group 2 over Groups 4-6; Group 3 over Groups 5-6; Group 4 over Groups 5-6; and Group 5 over Group 6 (see Supplementary Appendix 4, tab “Summary_Cases15_ETR_exist”). The same analysis was done for Pf malaria cases among all ages (0-99 years) in HTR areas for the existing network of CHWs (see Supplementary Appendix 4, tab “Summary_Cases15_HTR_exist”), Pf malaria cases among all ages (0-99 years) in ETR areas for the hypothetical network (see Supplementary Appendix 4, tab “Summary_Cases15_ETR_hypo”), and Pf malaria cases among all ages (0-99 years) in HTR areas for the hypothetical network (see Supplementary Appendix 4, tab “Summary_Cases15_HTR_hypo”).

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