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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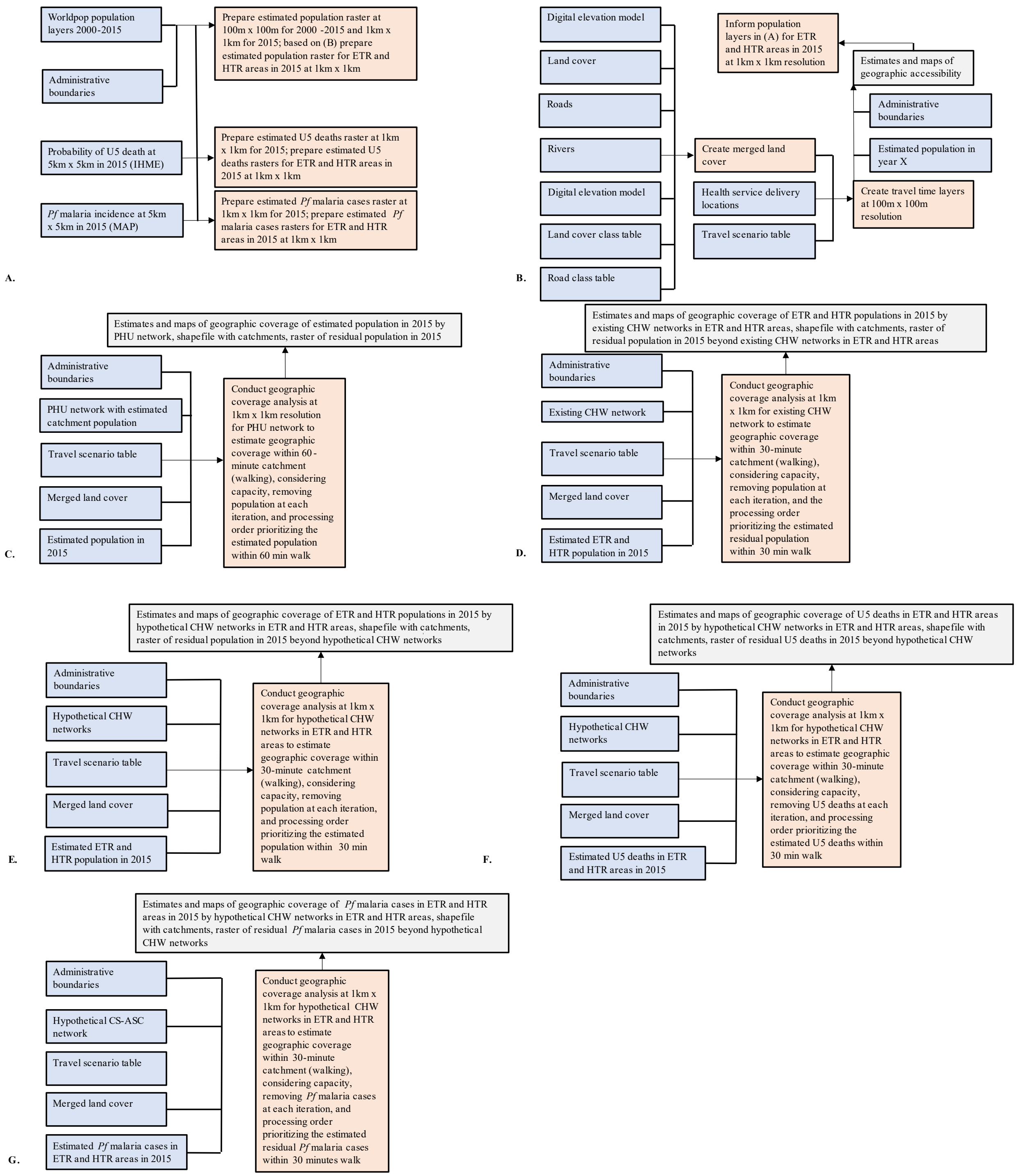
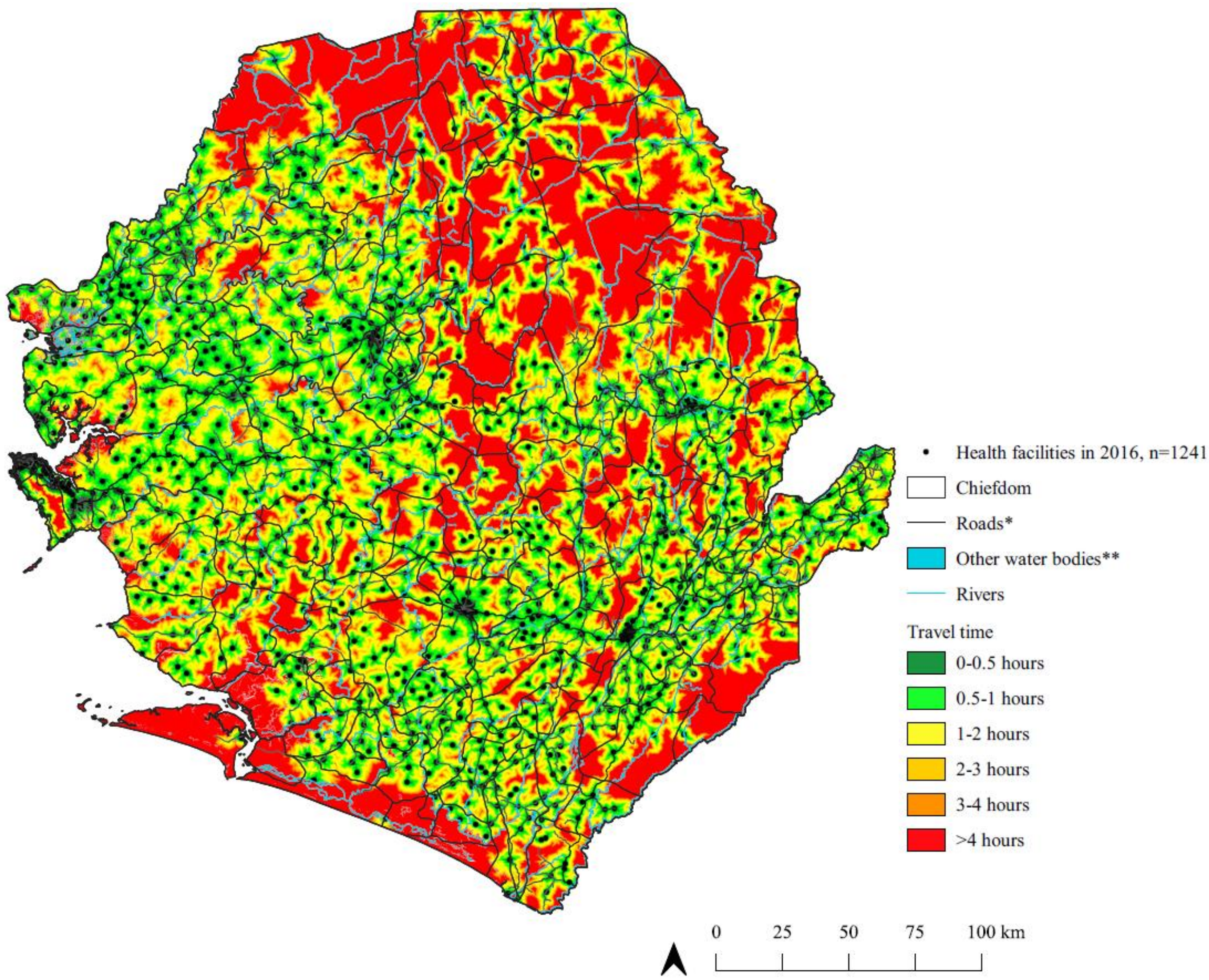
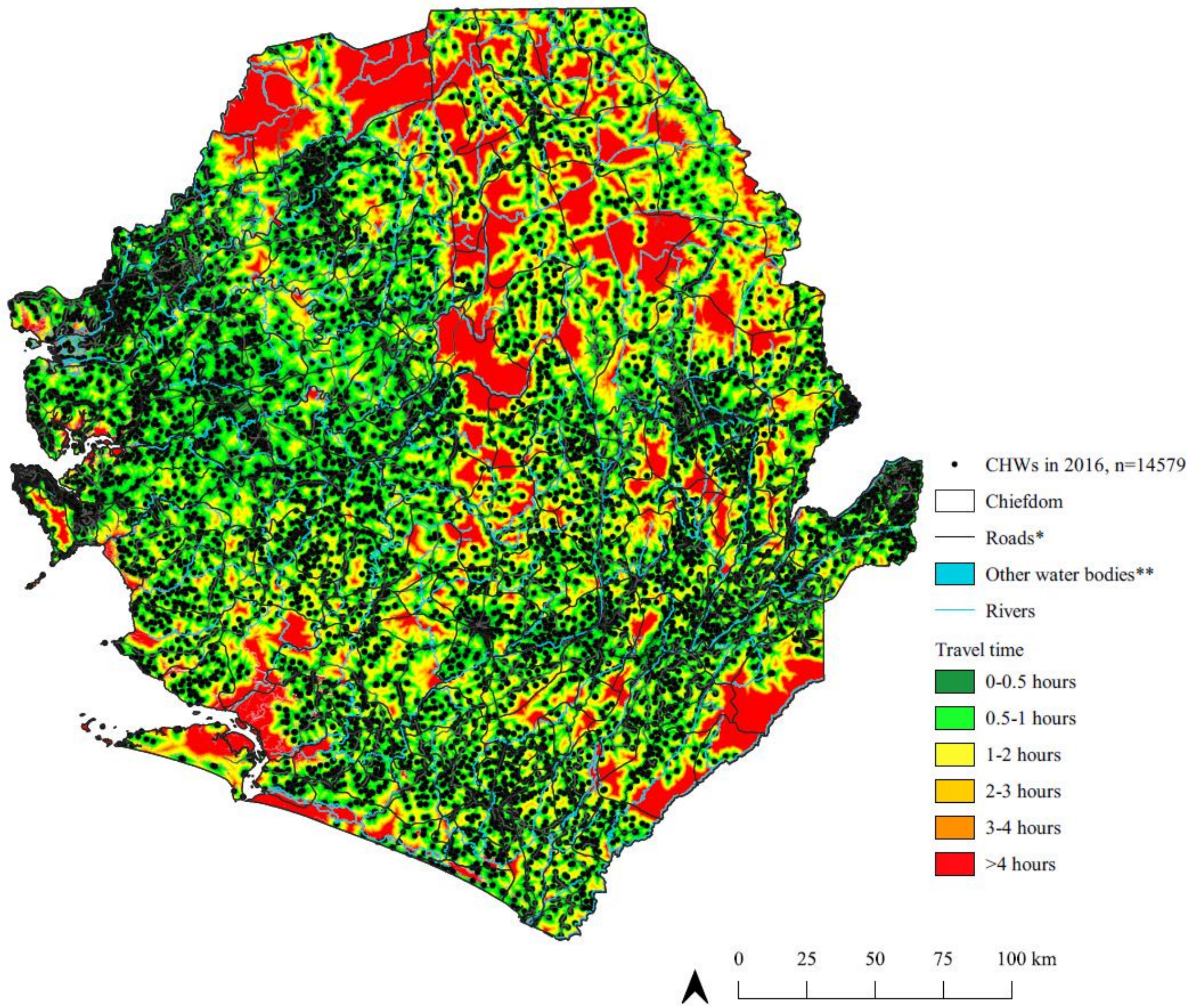


Supplementary Figure 1. Simplified analysis flow diagram

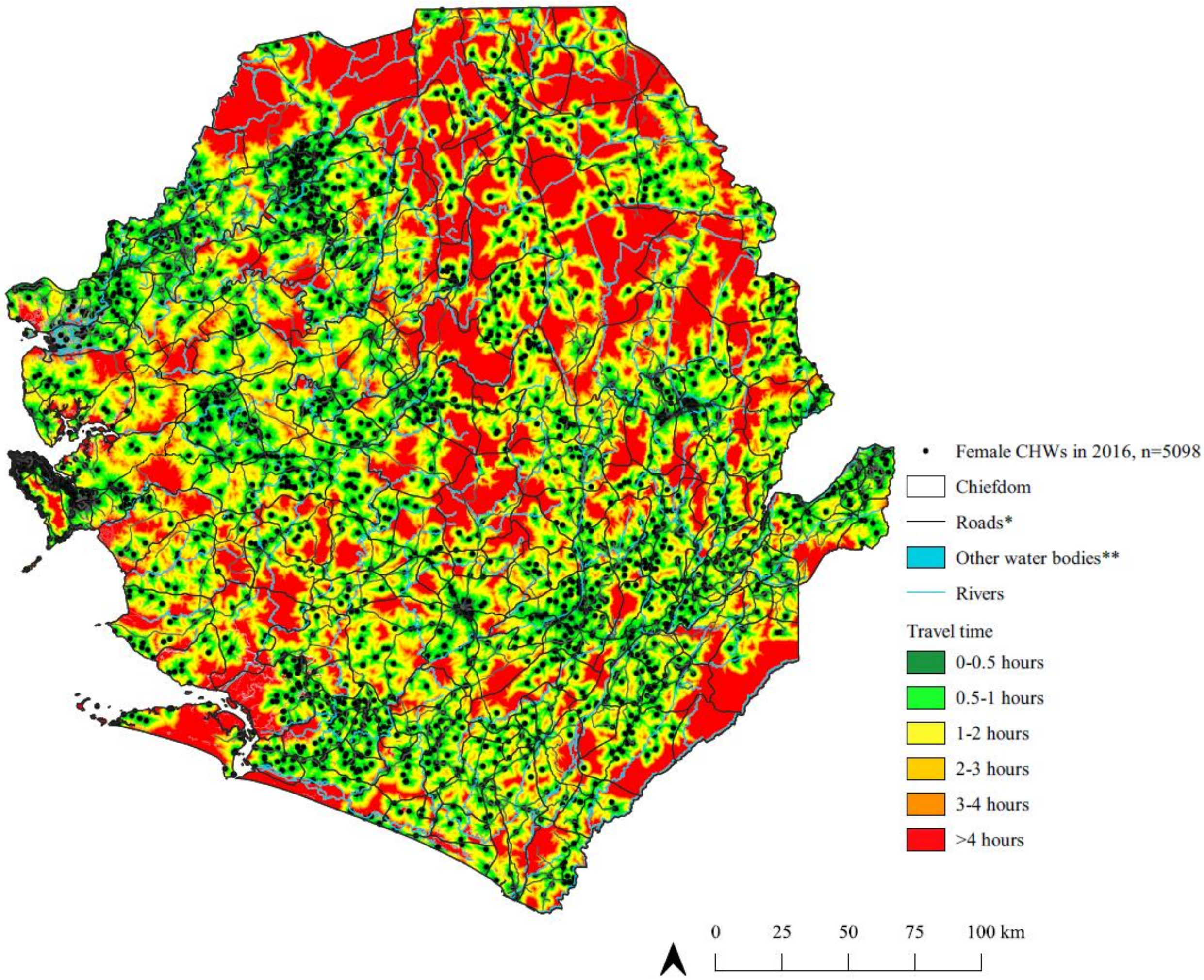
(A) Analysis flow for preparation of estimated population layers 2000-2015, estimated U5 deaths layers, and estimated *Pf* malaria cases layers. (B) Analysis flow for estimates and maps of geographic accessibility. (C) Analysis flow for estimates and maps of geographic coverage of the estimated population in 2015 by the PHU network at 1km x 1km resolution. (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 at 1km x 1km resolution. (E) Analysis flow for estimates and maps of geographic coverage of the estimated ETR and HTR populations in 2015 by hypothetical CHW networks deployed to ETR and HTR areas to optimise geographic coverage of the estimated ETR and HTR populations at 1km x 1km resolution. (F) Analysis flow for estimates and maps of geographic coverage of the estimated U5 deaths in ETR and HTR areas in 2015 by hypothetical CHW networks deployed to ETR and HTR areas to optimise geographic coverage of the estimated U5 deaths in ETR and HTR areas at 1km x 1km resolution. (G) Analysis flow for estimates and maps of geographic coverage of the estimated *Pf* malaria cases in ETR and HTR areas in 2015 by hypothetical CHW networks deployed to ETR and HTR areas to optimise geographic coverage of the estimated *Pf* malaria cases in ETR and HTR areas at 1km x 1km resolution. Blue boxes represent data inputs. Orange boxes represent analysis steps. Grey boxes represent outputs. IHME = Institute for Health Metrics and Evaluation. MAP = Malaria Atlas Project. U5 = children under-five years of age. *Pf* = *Plasmodium falciparum.*



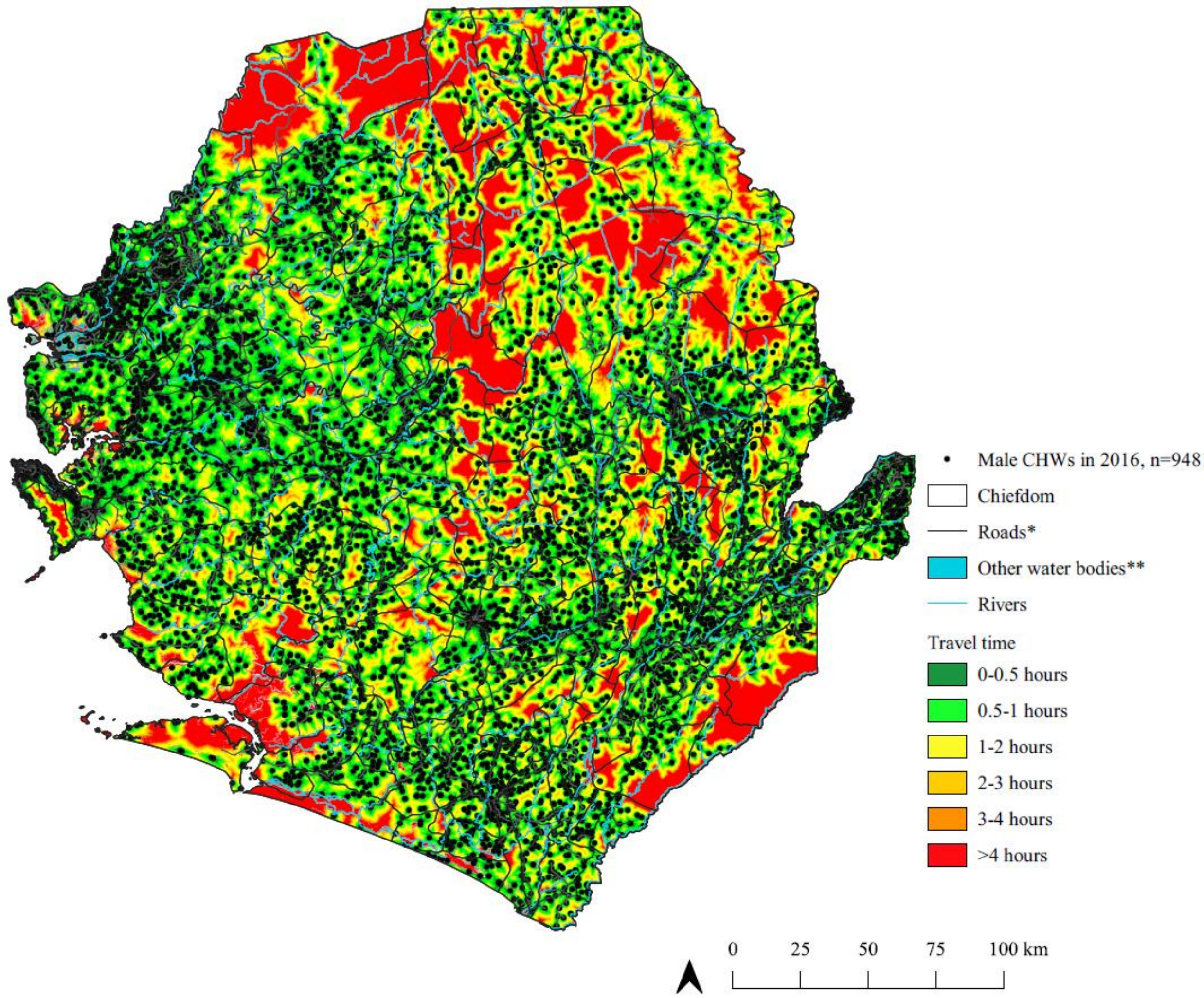
Supplementary Figure 2. Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest health facility in 2016. A) Health facilities, including hospitals and PHUs (community health centre (CHC), community health posts (CHP), maternal and child health posts (MCHP), and clinics) in 2016, n=1241. *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.



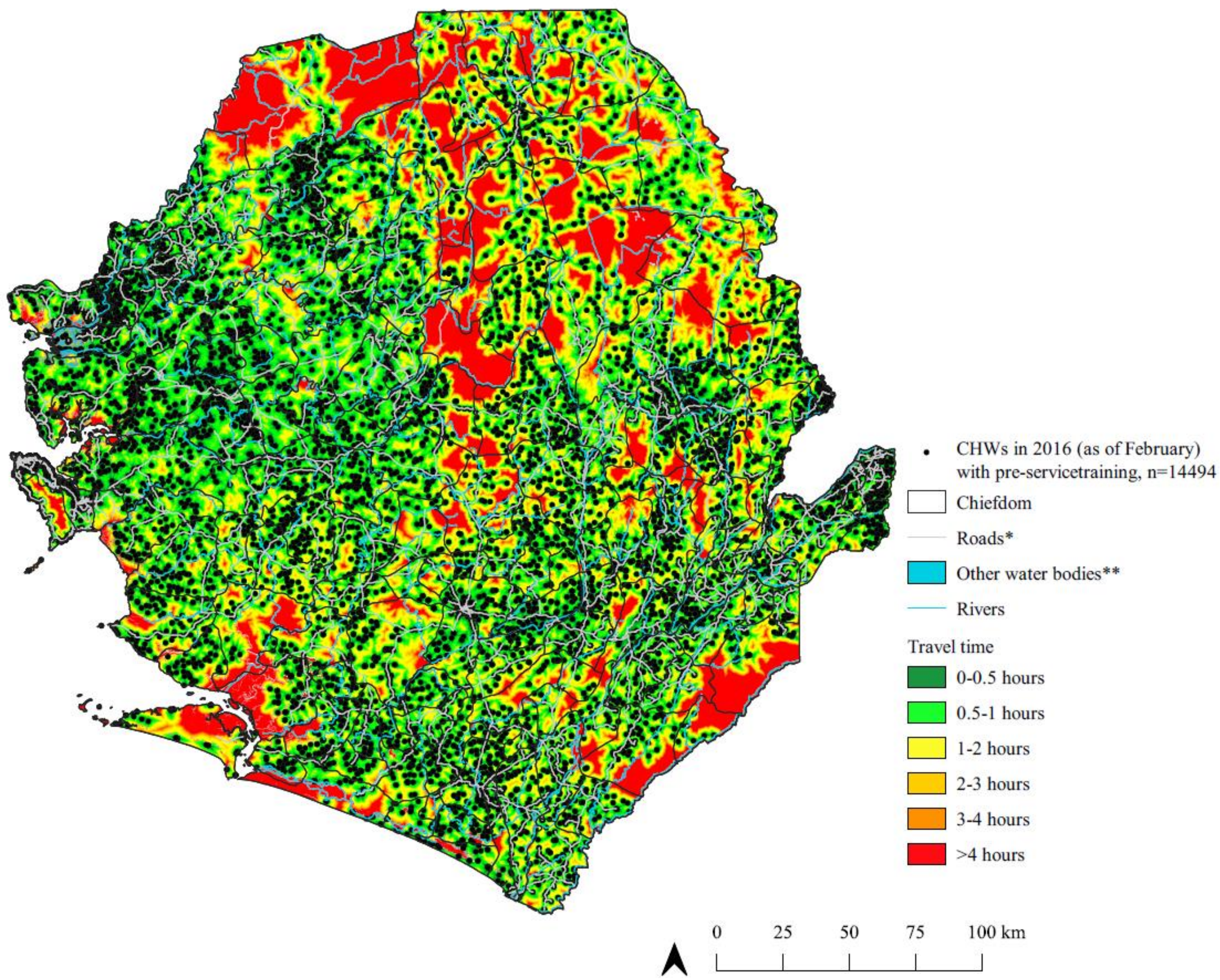
Supplementary Figure 3. Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest CHW in 2016. Community health workers (CHW) in 2016, n=14579. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.



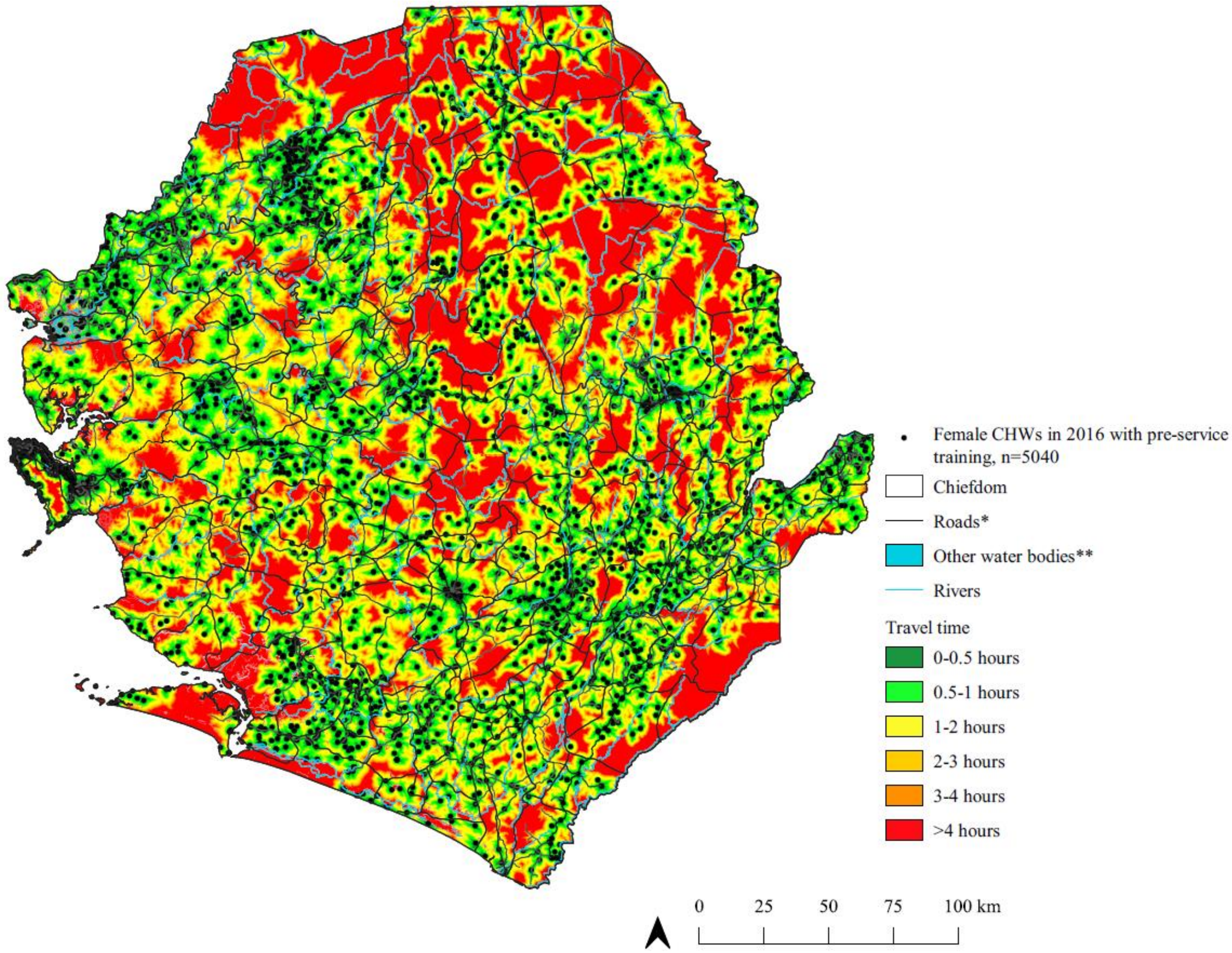
Supplementary Figure 4. Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest female CHW in 2016. Female CHWs in 2016, n=5098. CHW=community health worker. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.



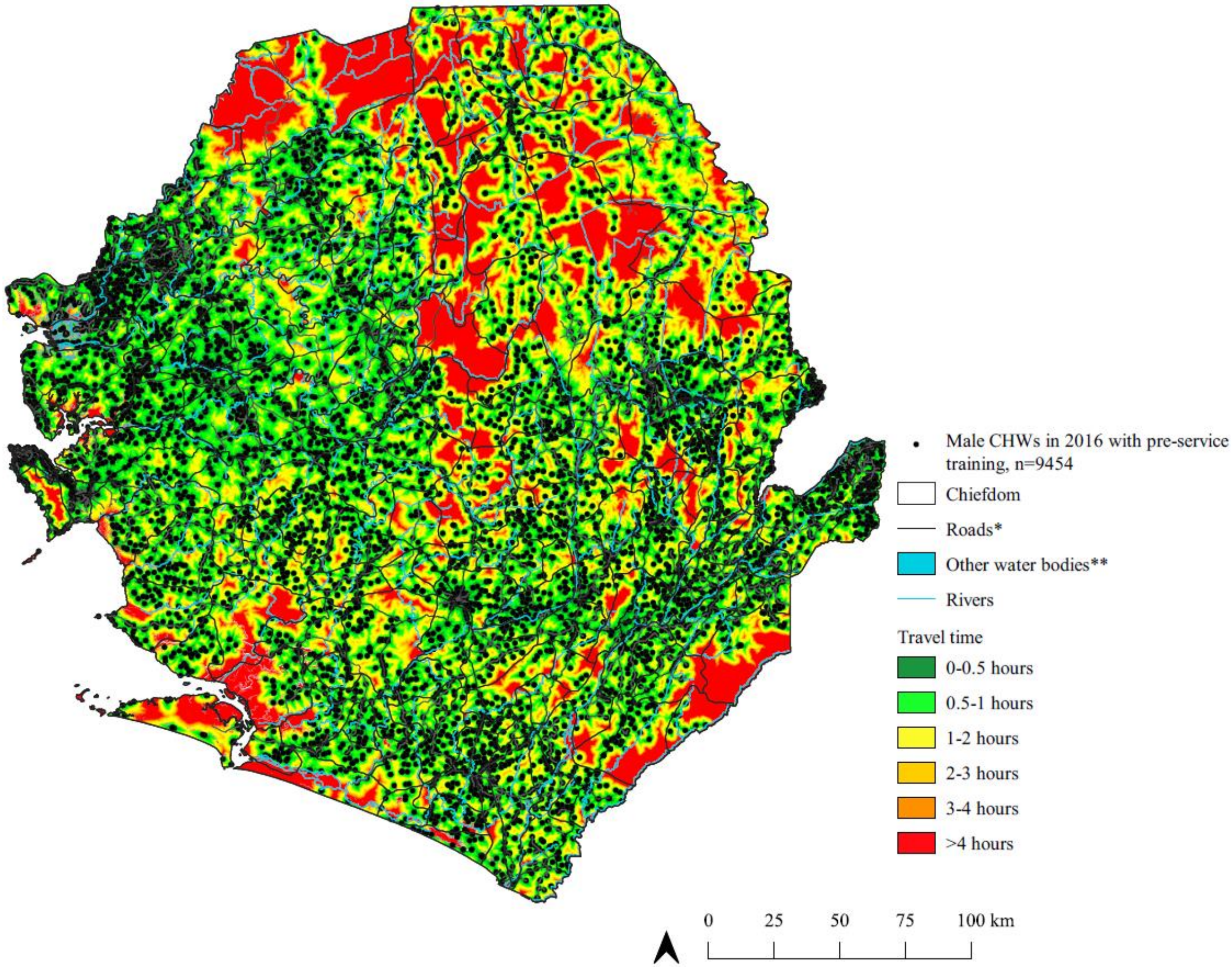
Supplementary Figure 5. Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest male CHW in 2016. Male CHWs in 2016, n=9481. CHW=community health worker. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands



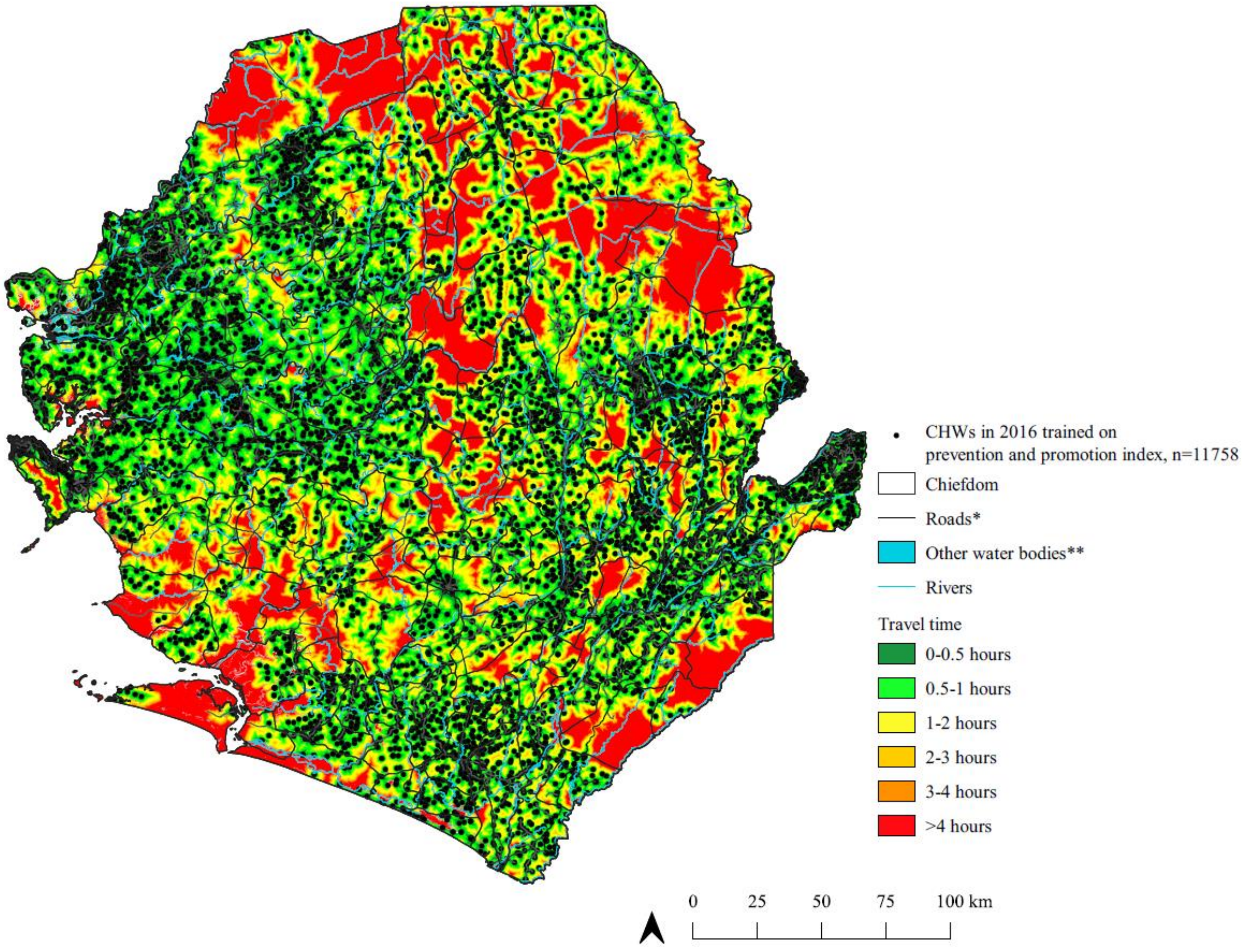
Supplementary Figure 6. Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest CHW in 2016 with pre-service training. Community health workers (CHW) in 2016 with pre-service training, n=14579. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.



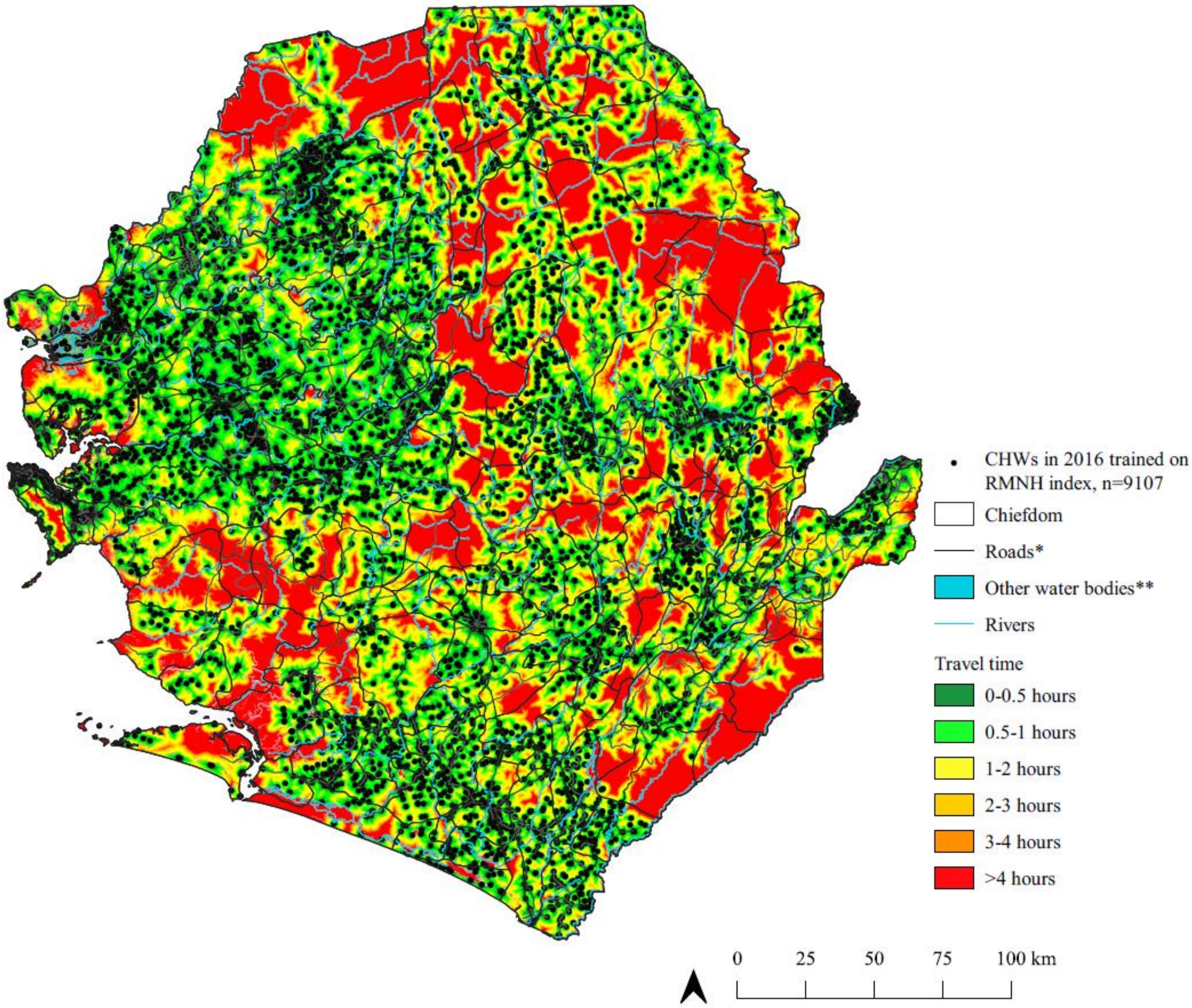
Supplementary Figure 7. Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest female CHW in 2016 with pre-service training. Female CHWs in 2016 with pre-service training, n=5040. CHW=community health worker. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.



Supplementary Figure 8. Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest male CHW in 2016 with pre-service training. Male CHWs in 2016 with pre-service training, n=9454. 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 9. Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest CHW in 2016 with pre-service training and trained on prevention and promotion interventions. CHW in 2016 with pre-service training and trained on an index of prevention and promotion interventions, including promotion of hygiene and sanitation, promotion of infant and young child feeding, and communication skills, n=11758. 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 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.

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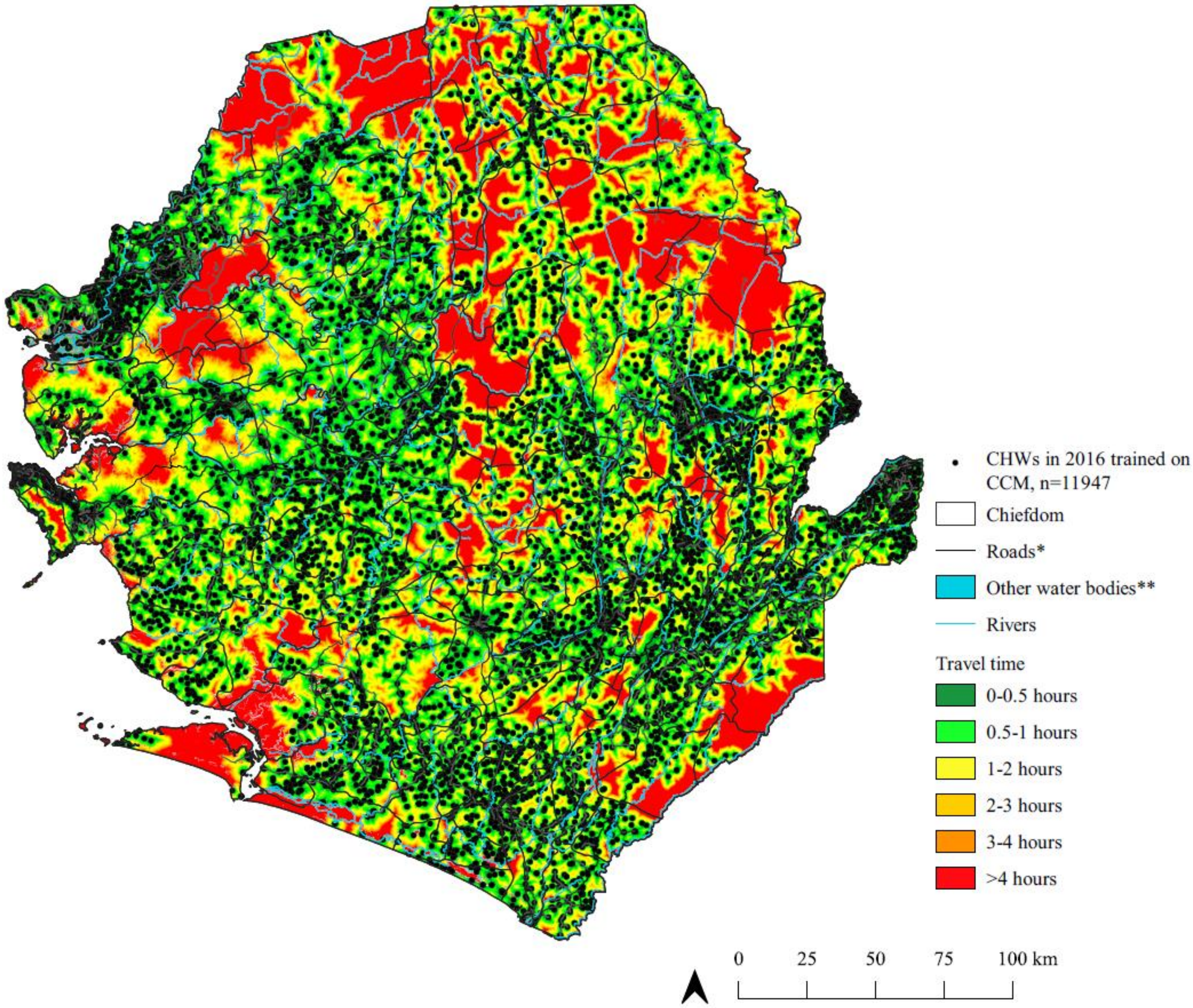
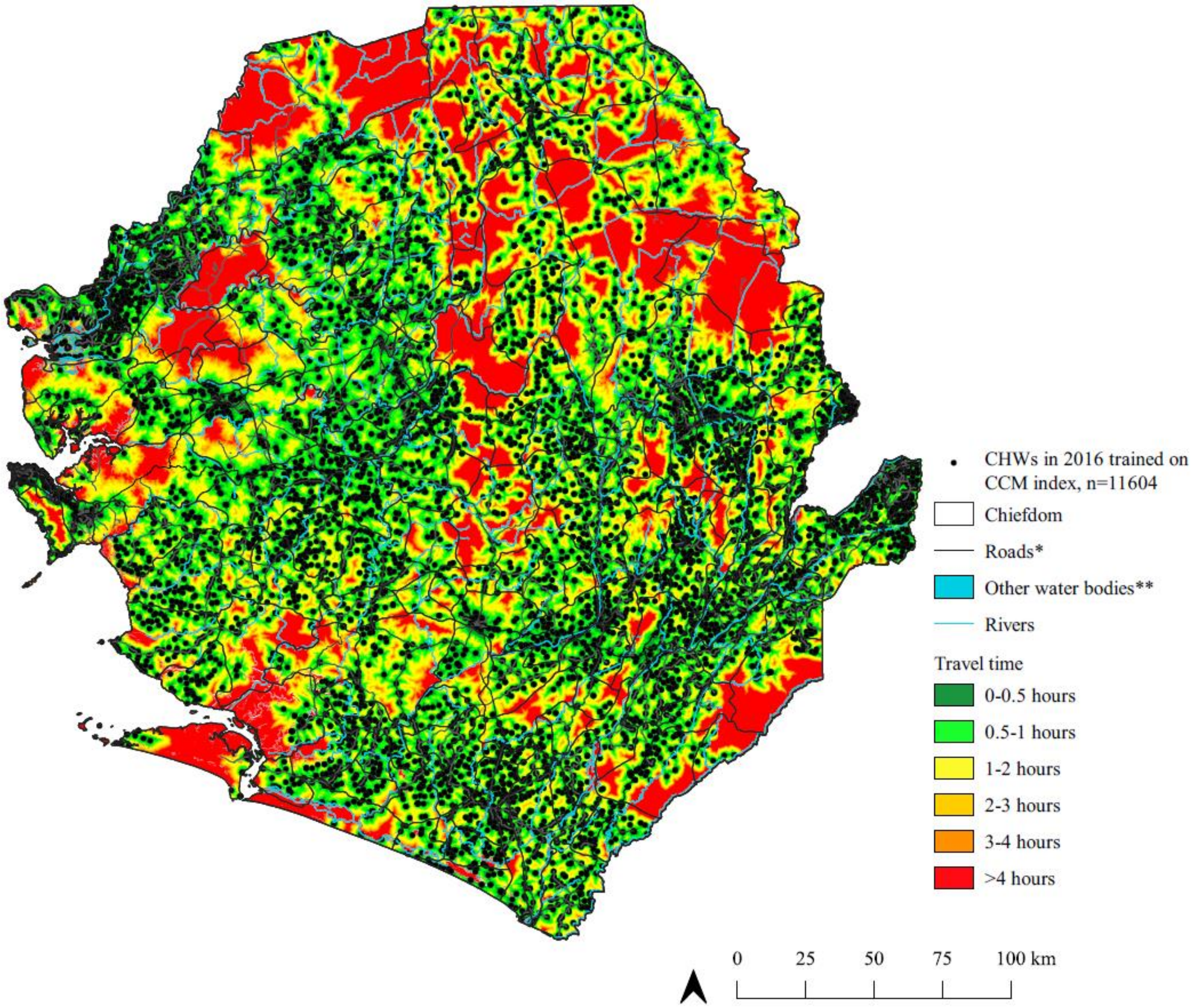
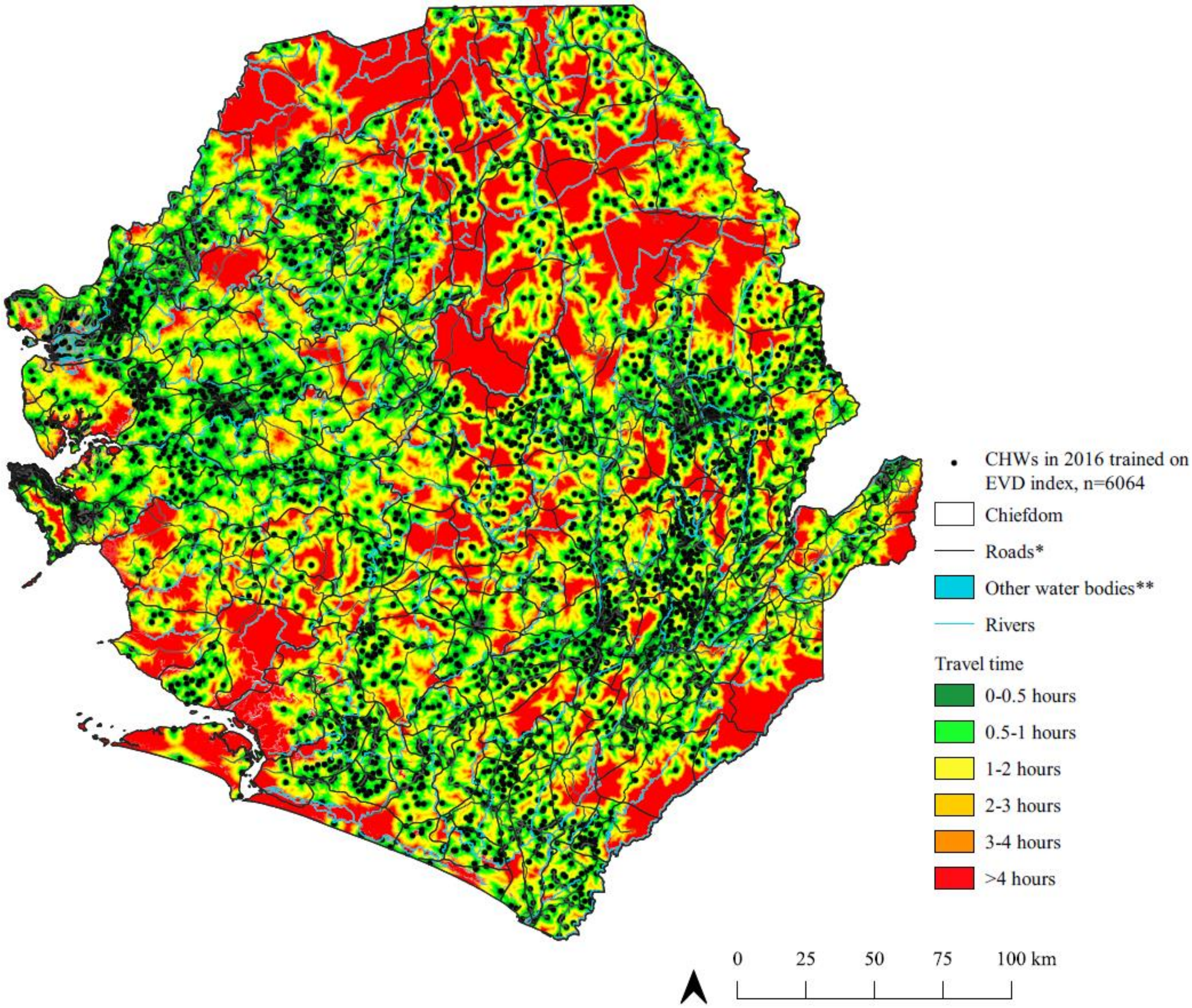


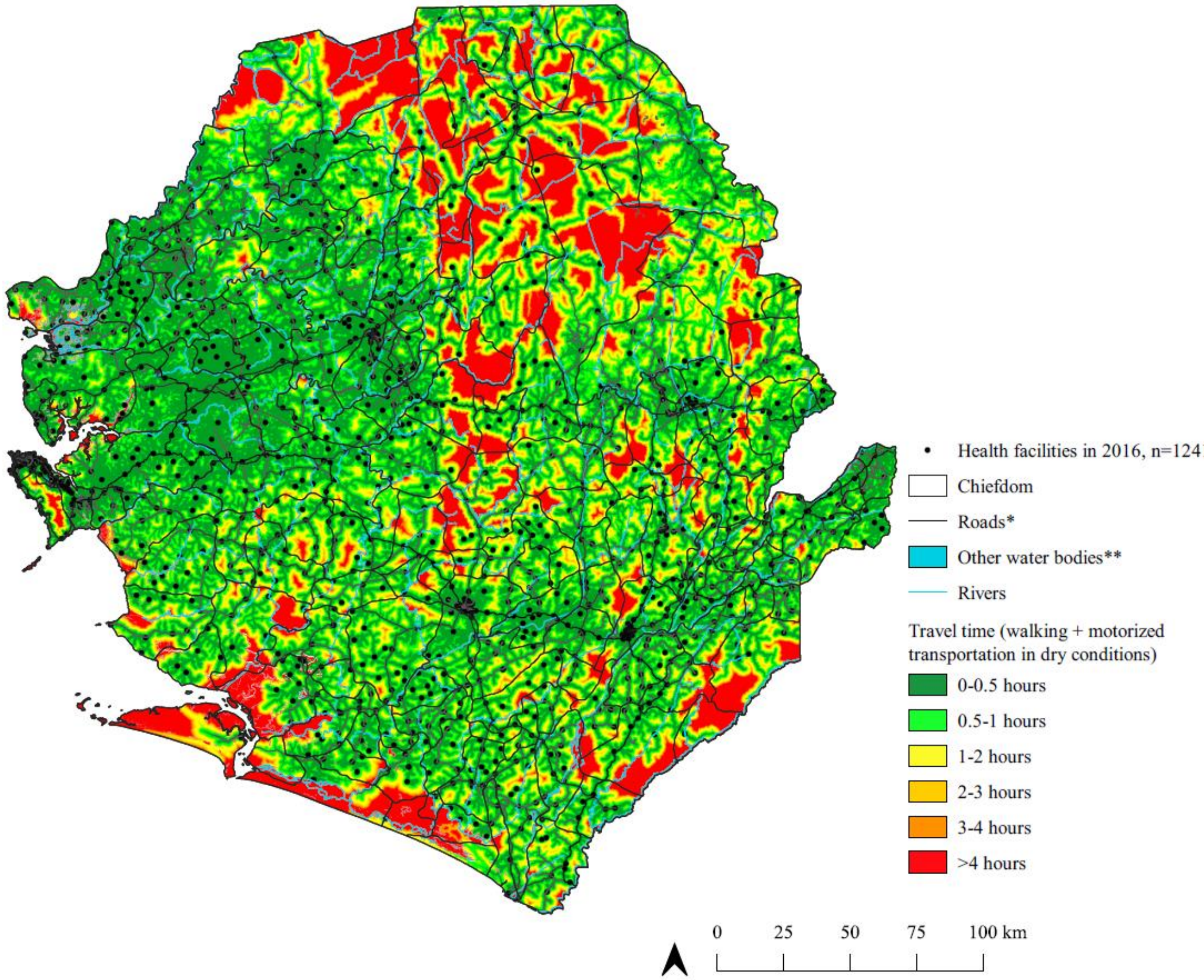
Supplementary Figure 11. Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest CHW in 2016 with pre-service training and trained on CCM for malaria. CHW in 2016 with pre-service training and trained on community case management (CCM) for malaria, n=11947. Note the 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.



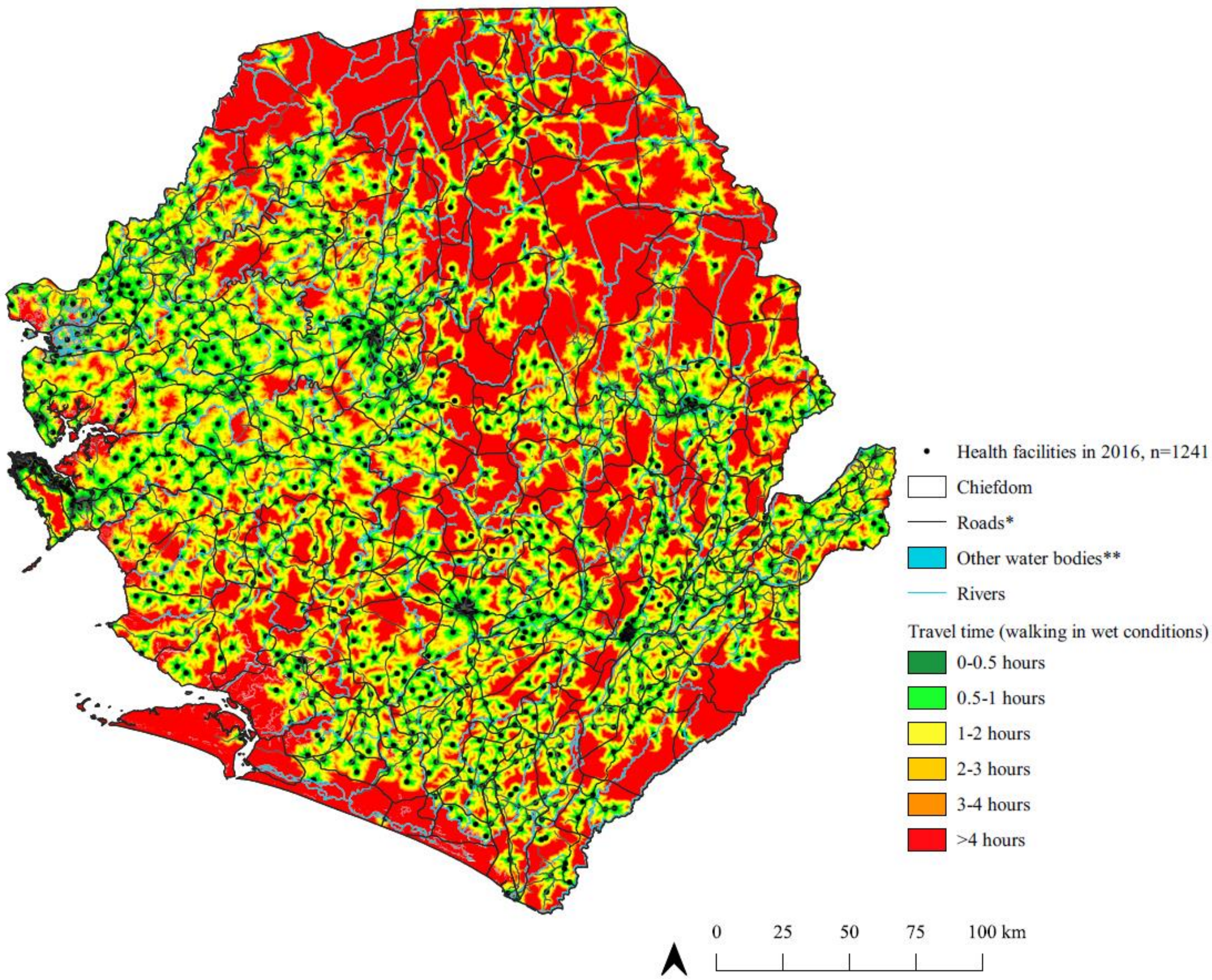
Supplementary Figure 12. Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest CHW in 2016 with pre-service training and trained on CCM for malaria and identification and referral of severe malnutrition. CHW in 2016 with pre-service training and trained on community 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.



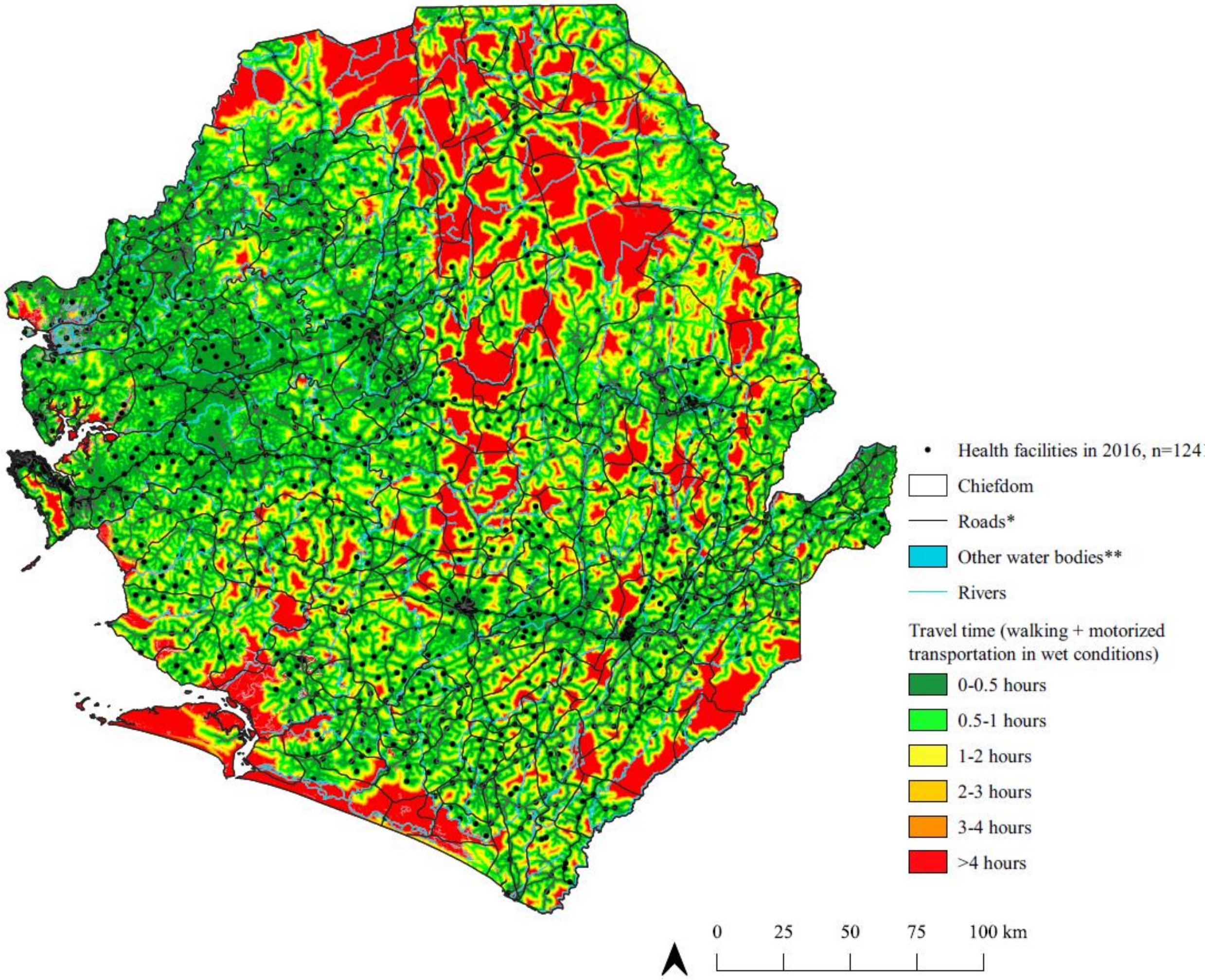
Supplementary Figure 13. Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest CHW in 2016 trained on EVD signal functions. CHW in 2016 with pre-service training and trained on Ebola virus disease (EVD) signal functions (contact tracing, identification and reporting on major signs/symptoms, social mobilization) n=6064. 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 14. Geographic accessibility (travel time in minutes, walking + motorised transportation in dry conditions) to the nearest health facility in 2016. Health facilities, including hospitals and PHUs (community health centre (CHC), community health posts (CHP), maternal and child health posts (MCHP), and clinics) in 2016, n=1241. *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 15. Geographic accessibility (travel time in minutes, walking in wet conditions) to the nearest health facility in 2016. Health facilities, including hospitals and PHUs (community health centre (CHC), community health posts (CHP), maternal and child health posts (MCHP), and clinics) in 2016, n=1241. *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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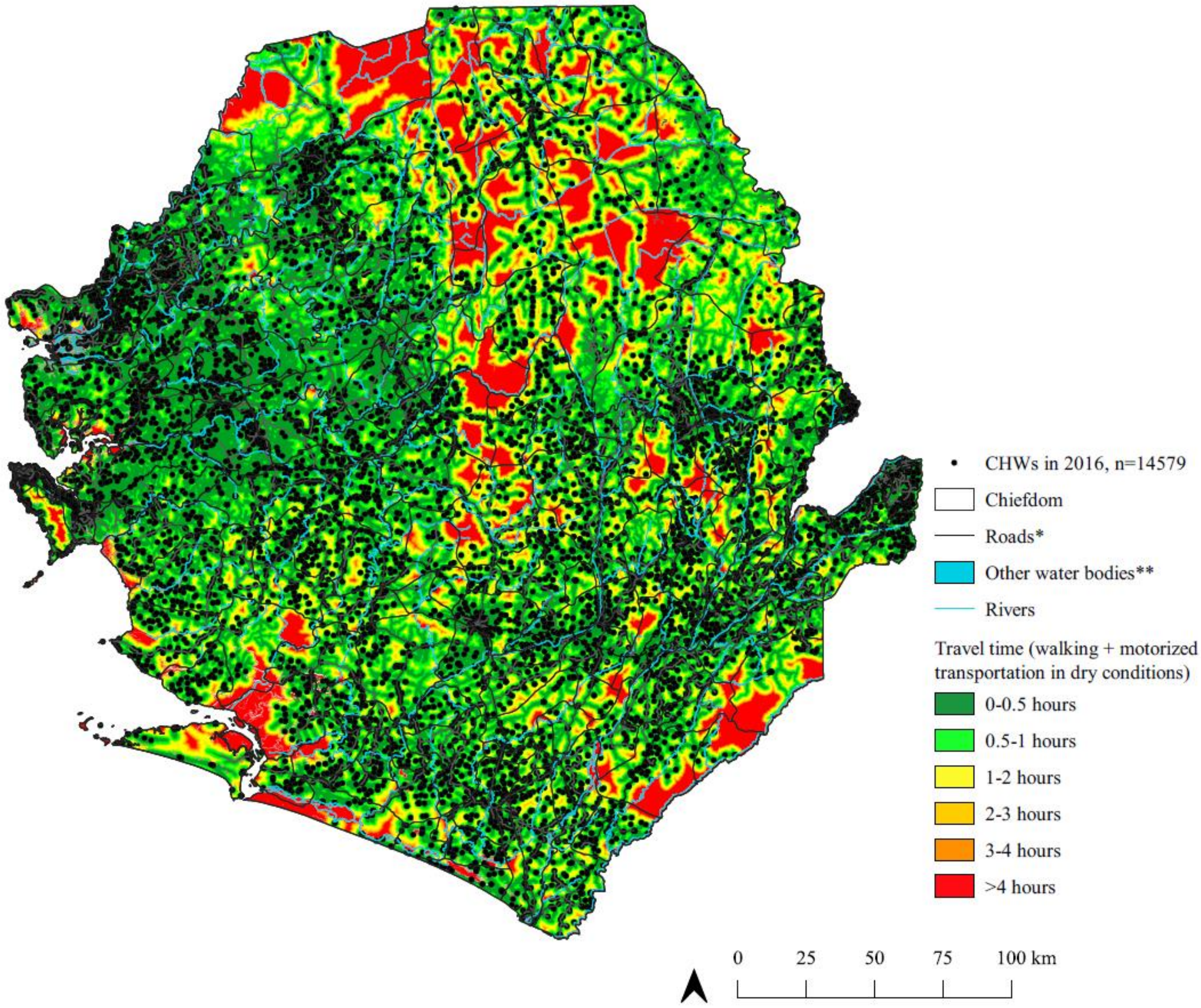
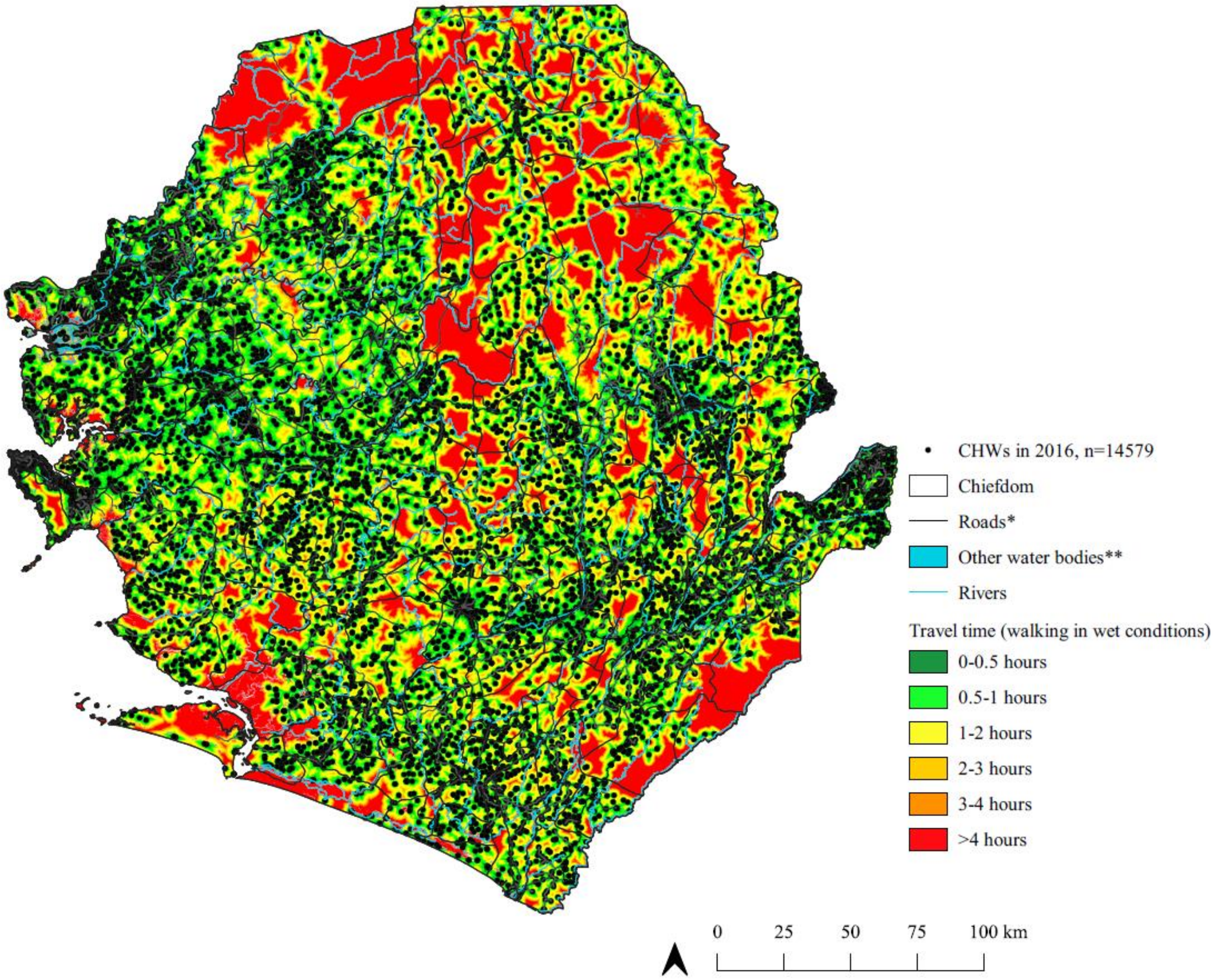
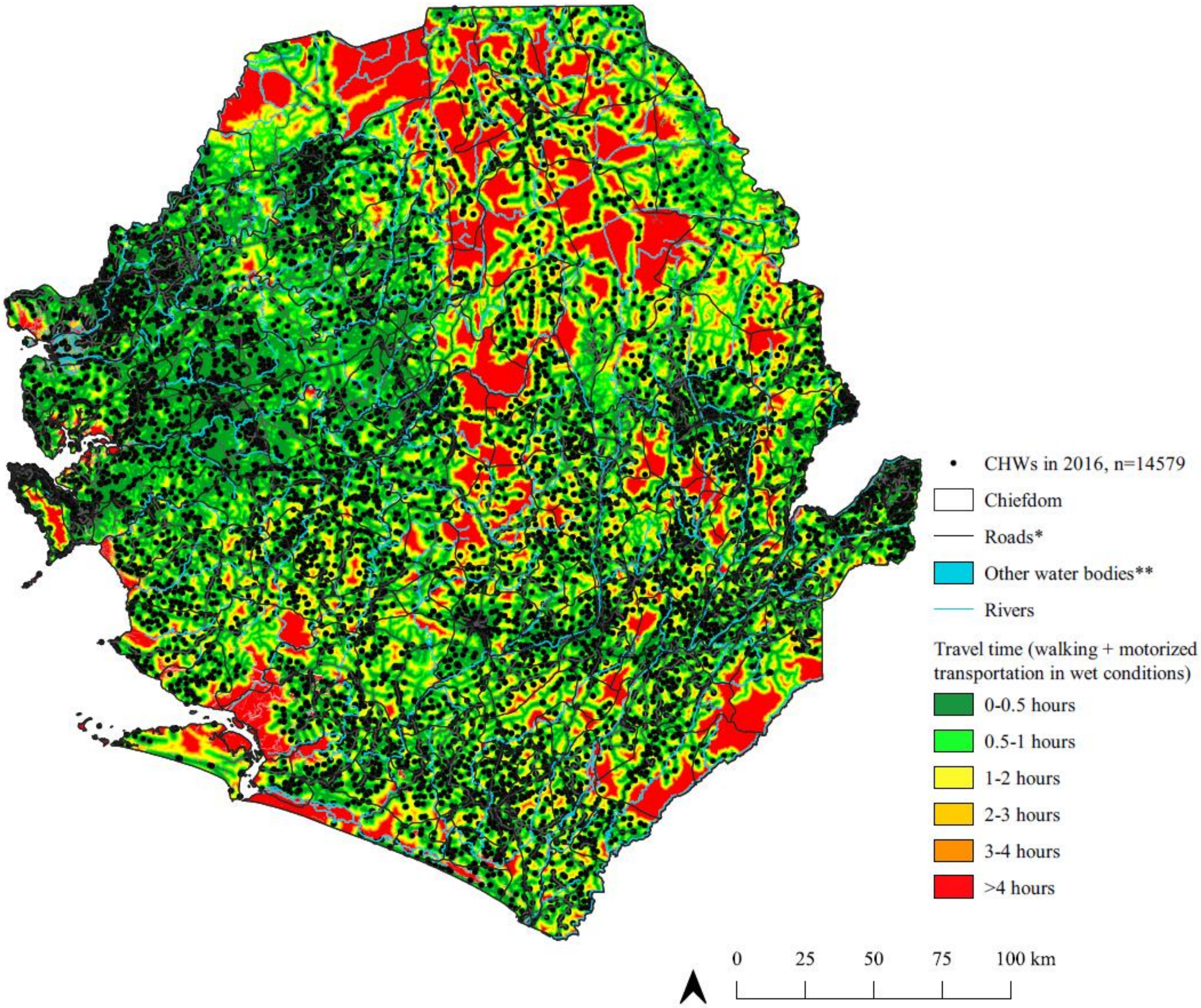


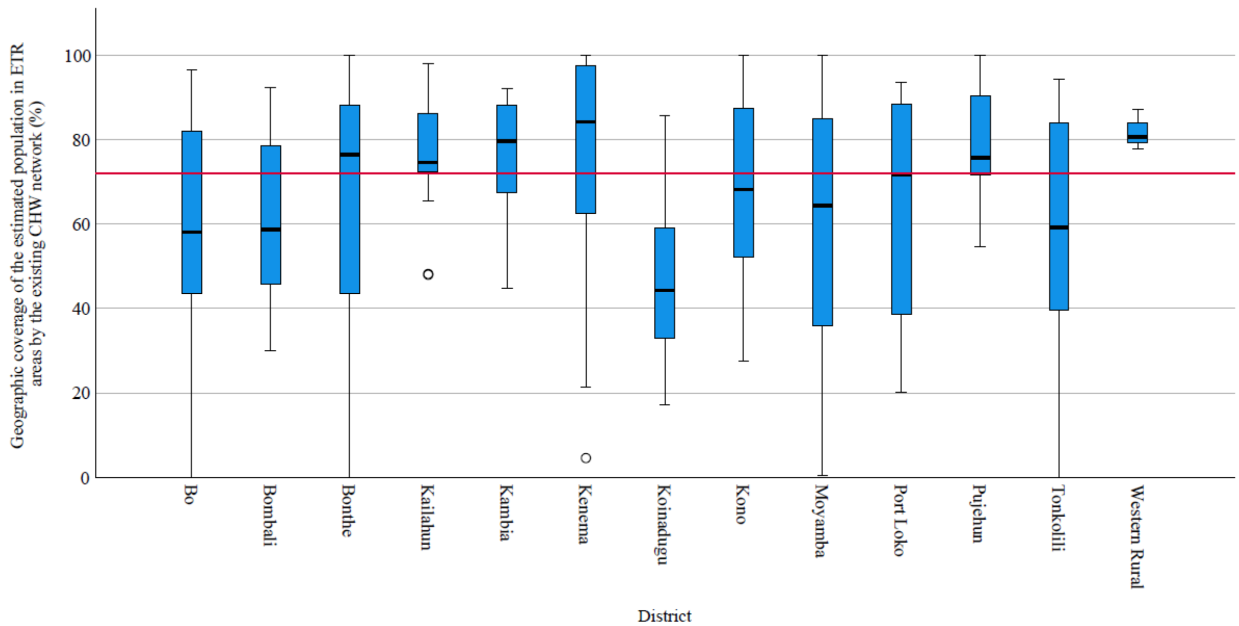
Supplementary Figure 17. Geographic accessibility (travel time in minutes, walking + motorised transportation in dry conditions) to the nearest CHW in 2016. Community health workers (CHW) in 2016, n=14579. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.



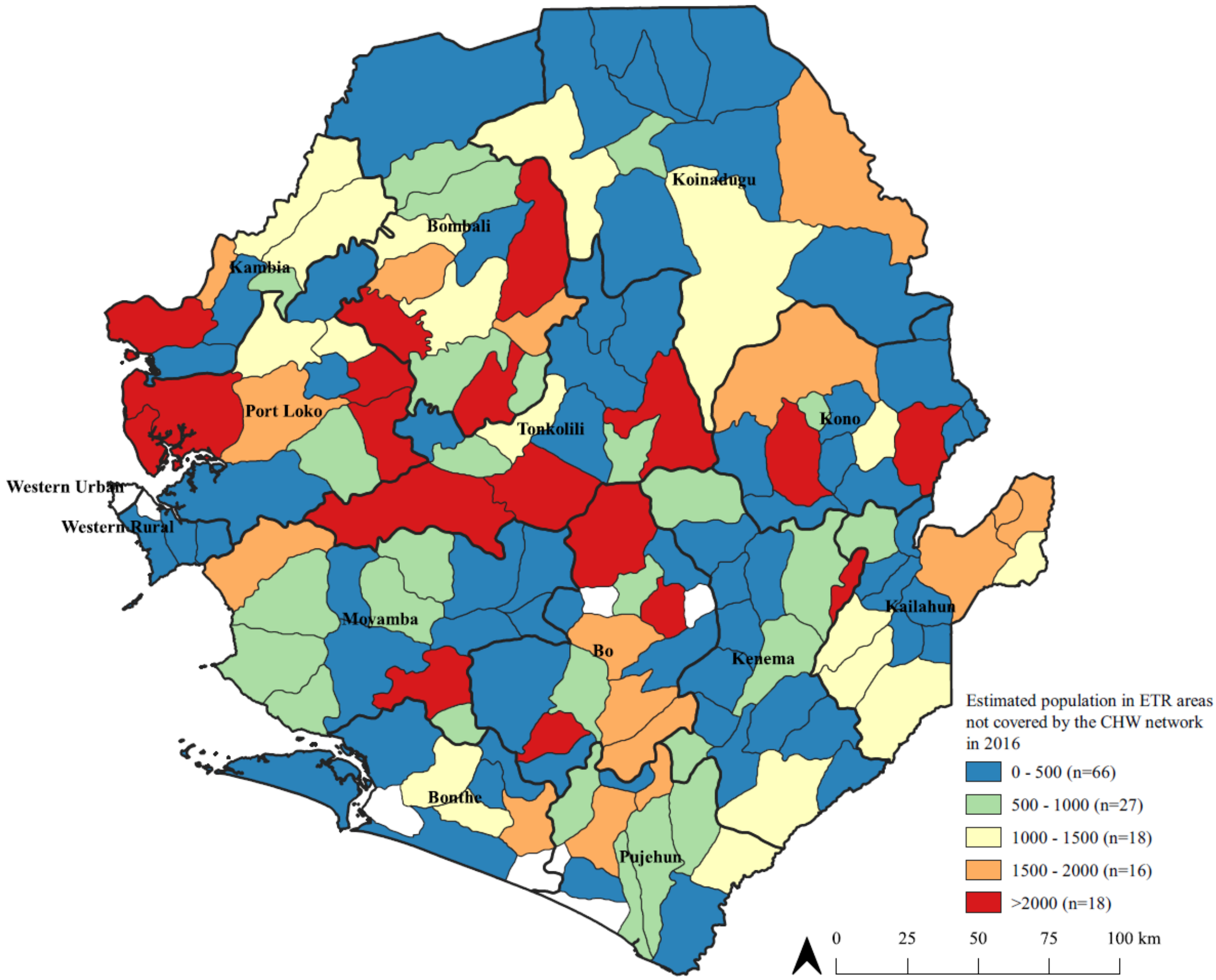
Supplementary Figure 18. Geographic accessibility (travel time in minutes, walking in wet conditions) to the nearest CHW in 2016. Community health workers (CHW) in 2016, n=14579. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.



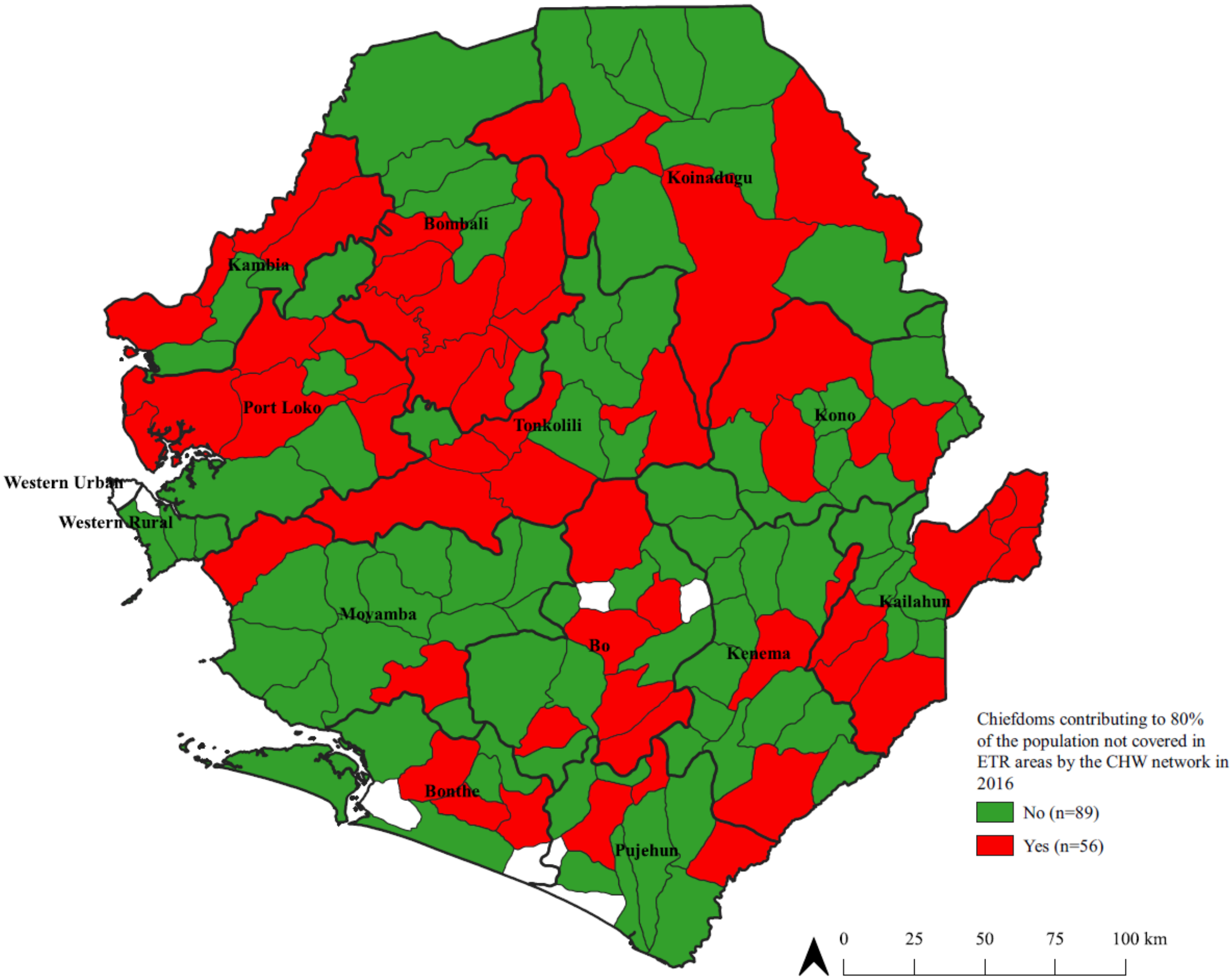
Supplementary Figure 19. Geographic accessibility (travel time in minutes, walking + motorised transportation in wet conditions) to the nearest CHW in 2016. Community health workers (CHW) in 2016, n=14579. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.



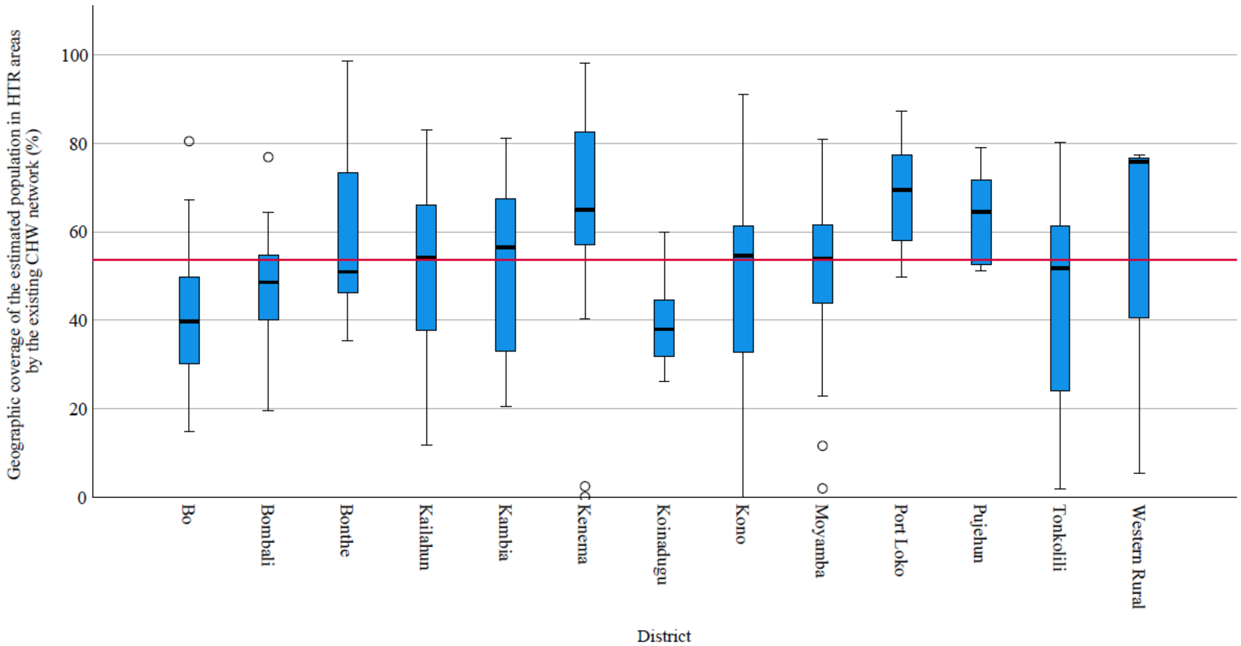
Supplementary Figure 20. Median and interquartile range of geographic coverage at chiefdom level (administrative level 3) of the estimated population in ETR areas by the existing network of CHWs, by district (administrative level 2). Median and interquartile range of geographic coverage at chiefdom level (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



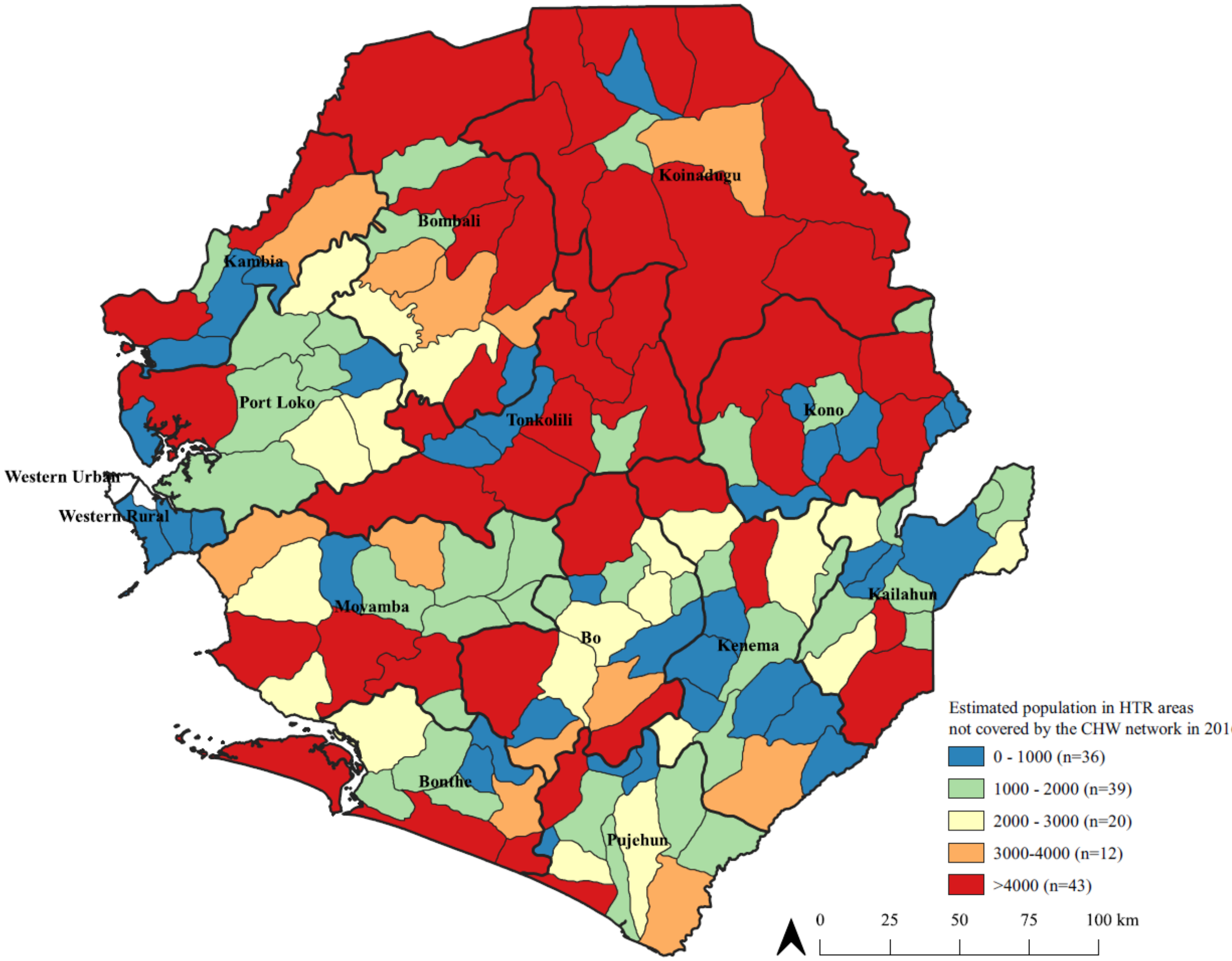
Supplementary Figure 21. Estimated population in ETR areas in 2015 not covered by the CHW network (30-minute catchment, walking) by chiefdom (administrative level 3). ETR=easy to reach. CHW=community health worker. Eight chiefdoms without ETR areas coloured white and excluded from analysis. Total districts = 153.



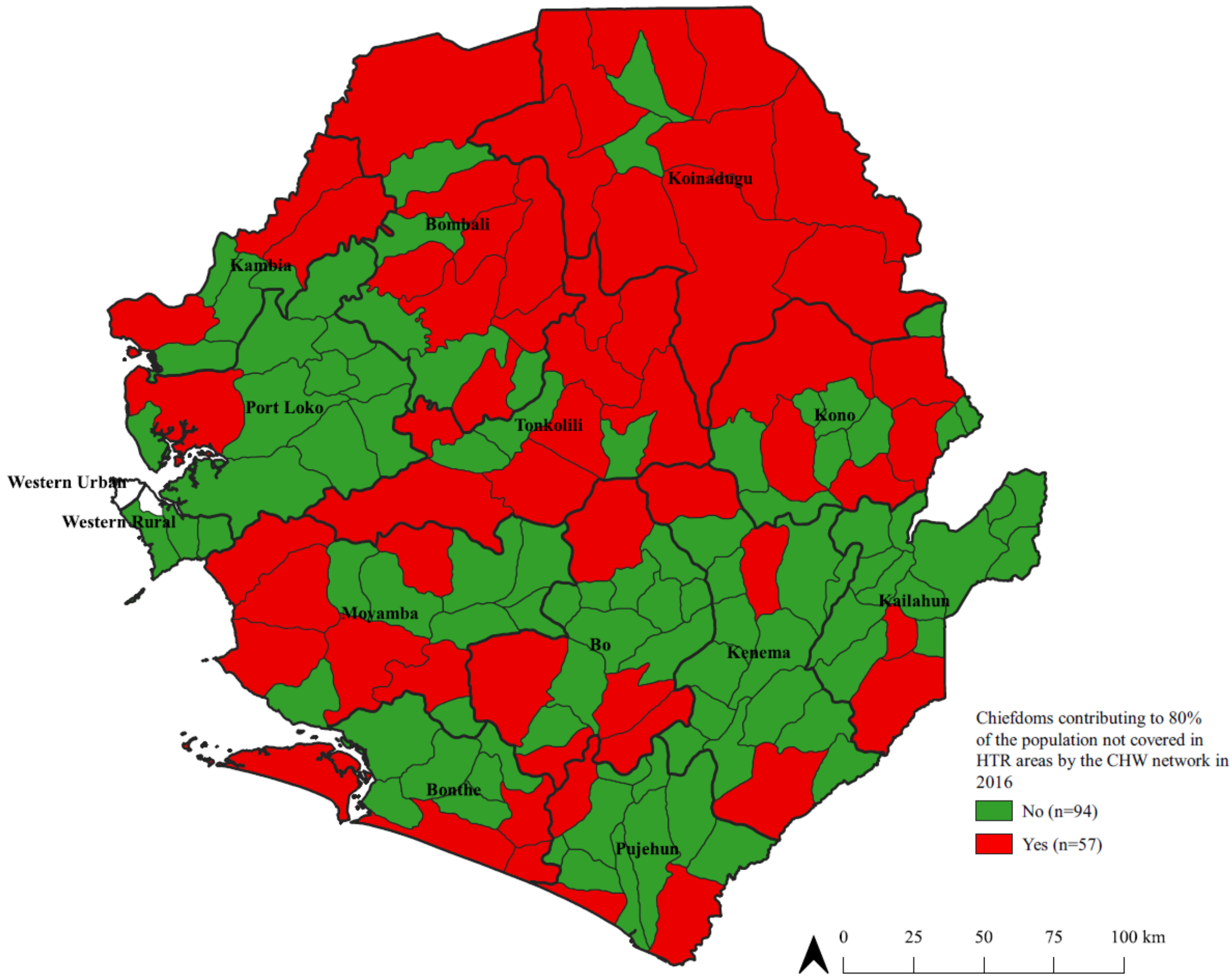
Supplementary Figure 22. Chiefdoms contributing to 80% of the estimated population in ETR not covered by the CHW network in 2016 (30-minute catchment, walking). ETR=easy to reach. CHW=community health worker. Eight chiefdoms without ETR areas coloured white and excluded from analysis. Total districts = 153.



Supplementary Figure 23. Median and interquartile range of geographic coverage at chiefdom level (administrative level 3) of the estimated population in HTR 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 HTR 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 HTR areas. HTR=easy to reach. CHW=community health worker



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.

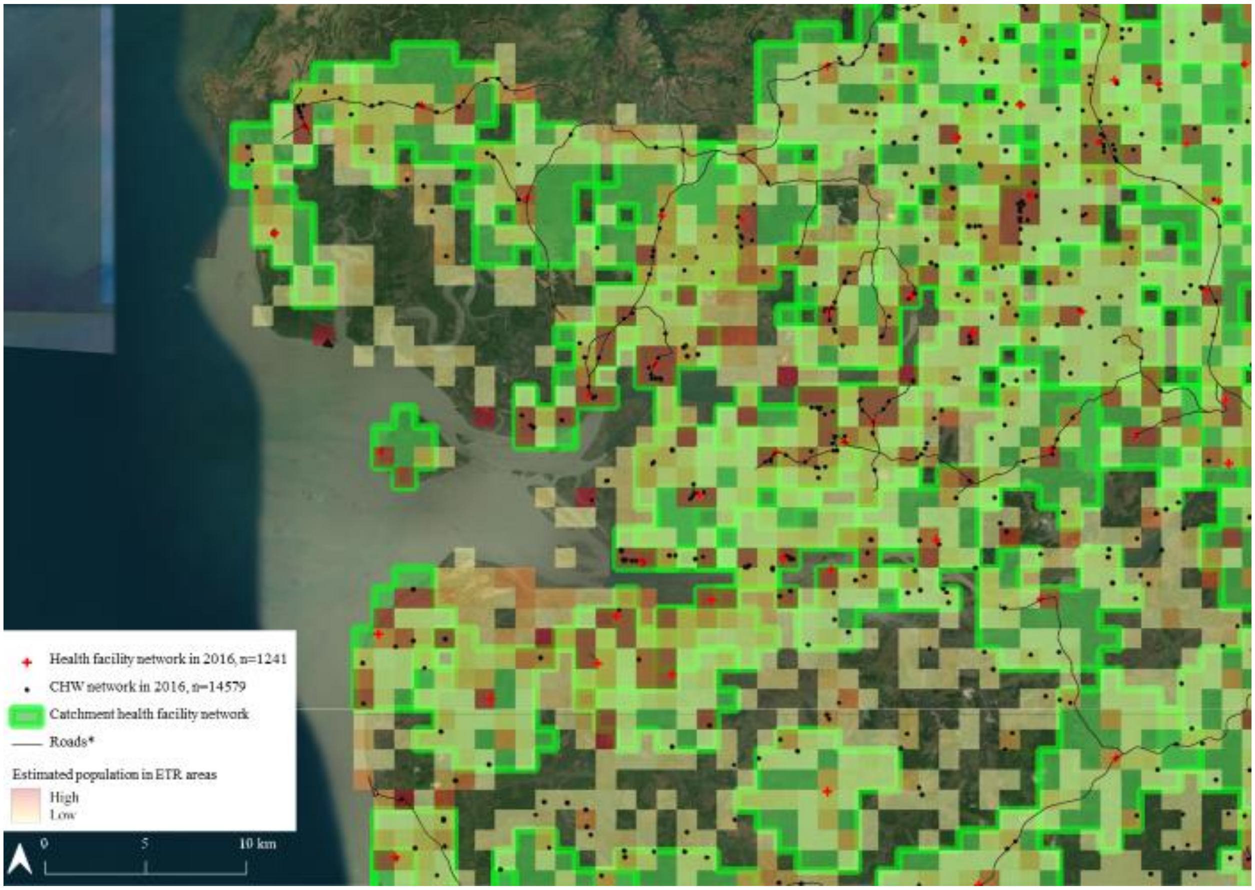
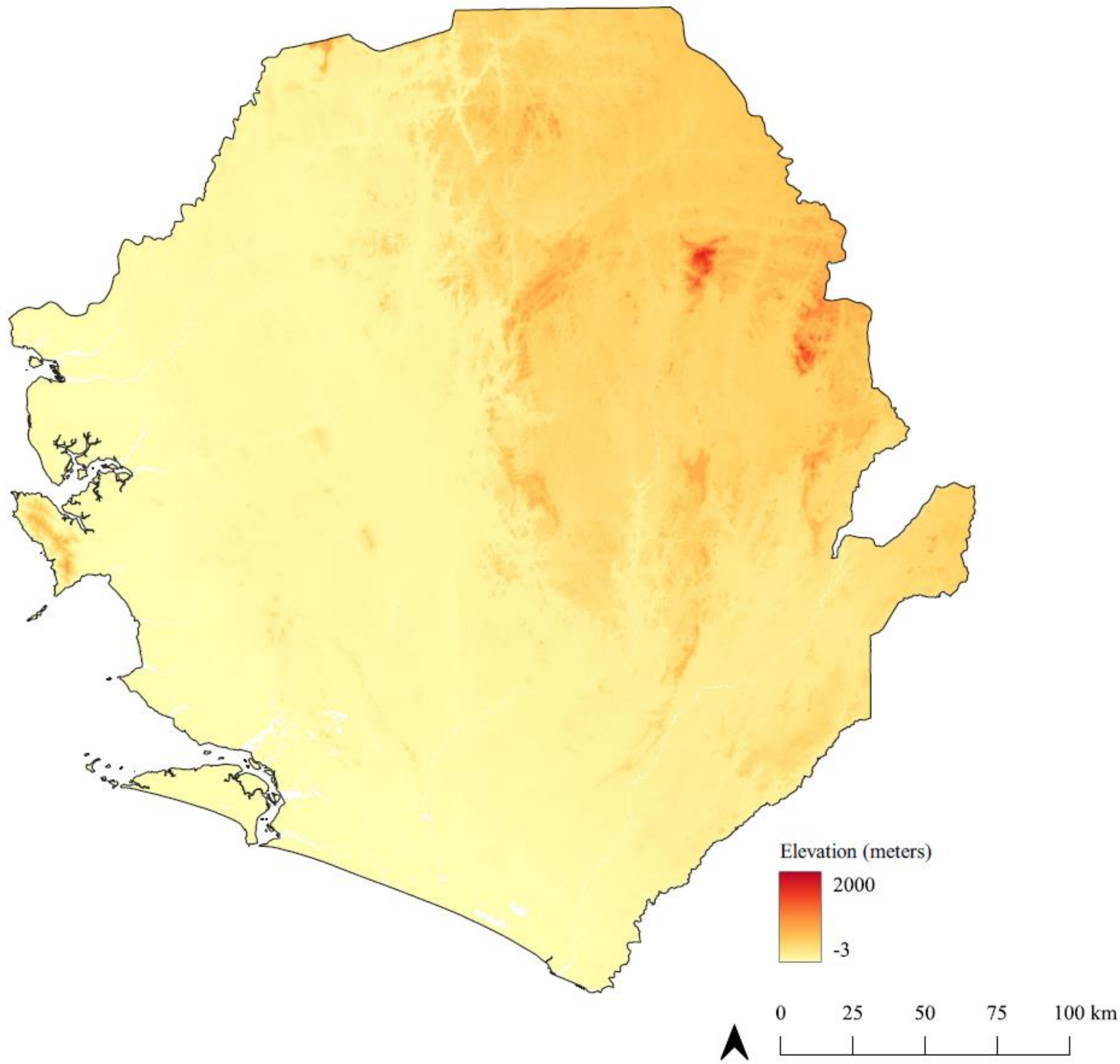
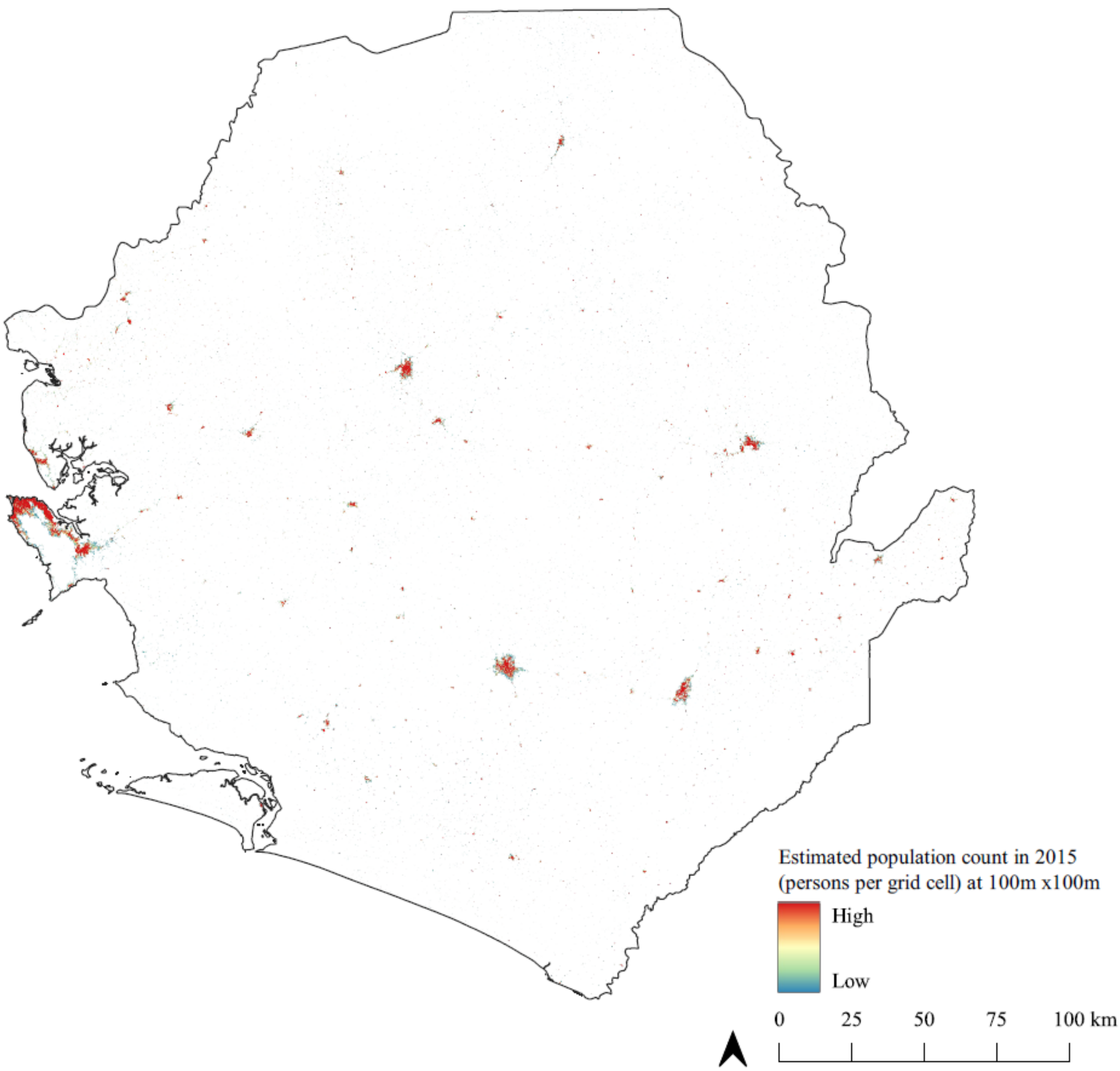


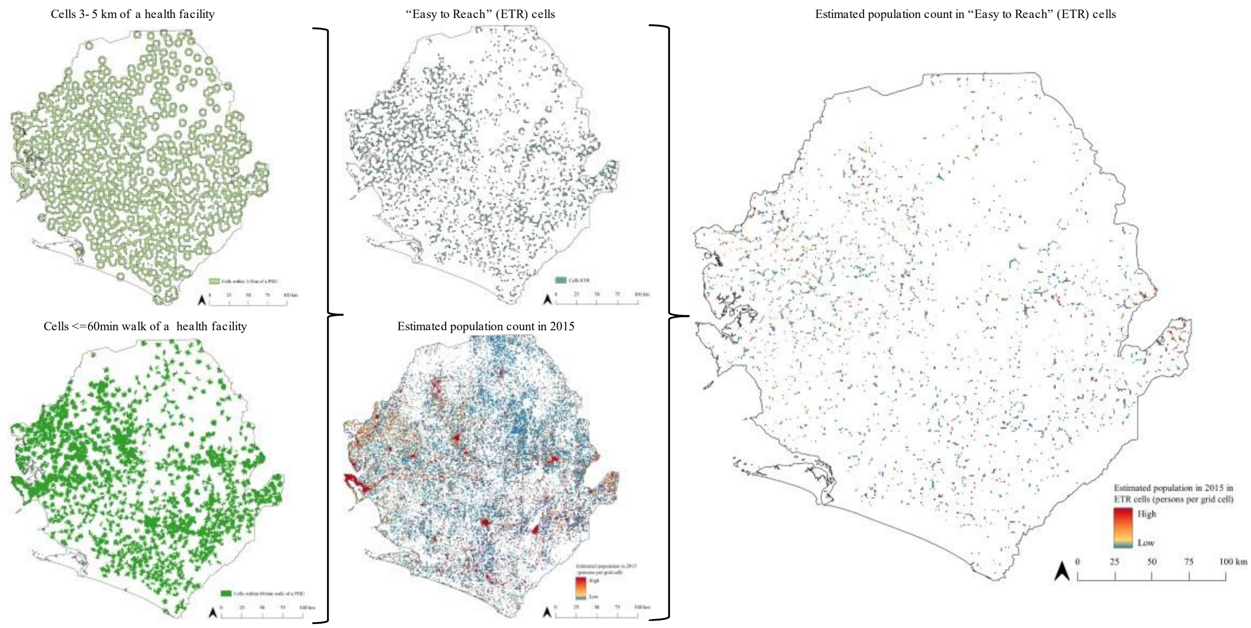
Figure 26. Modelled catchment areas of the health facility network, existing CHW network in ETR areas, and hypothetical CHW network in ETR areas in 2016 at 1km x 1km resolution. A) Modelled 60-minute catchment areas of the health facility network (green) in 2016 at 1km x 1km resolution based on a walking scenario and maximum population capacity according to MOHS norms. Images depict chiefdoms within Kambia and Port Loko districts in Northern province. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary.



Supplementary Figure 27. Digital elevation model at 100m x 100m resolution. NASA SRTMGL1 version 003 (approximately 30m x30m), resampled to 100m x 100m and 1km x 1km (later not shown). Accessed 13 August 2017.[1]

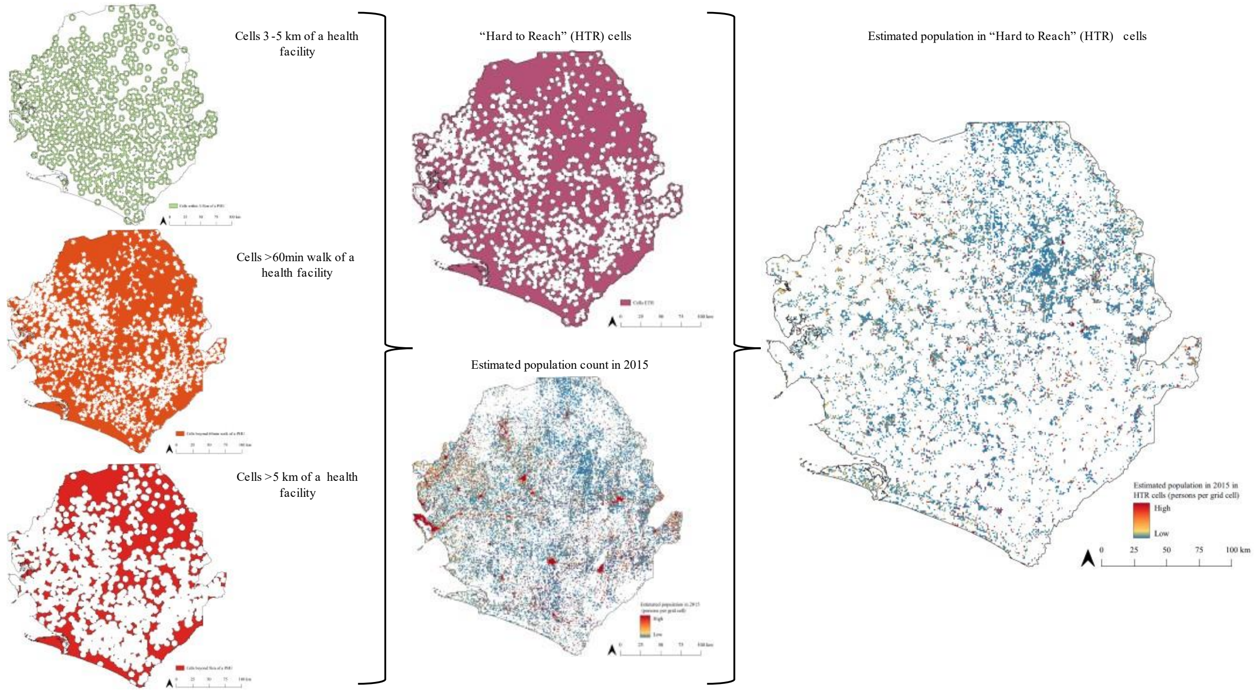


Supplementary Figure 28. Estimated population count in 2015 per grid cell at 100m x 100m resolution. Population layers produced at 100m x 100m resolution and 1km x 1km resolution resampled from Worldpop census disaggregated gridded population estimates at approximated 90m x 90m resolution for Sierra Leone in 2015, version 2.0. Worldpop[2]



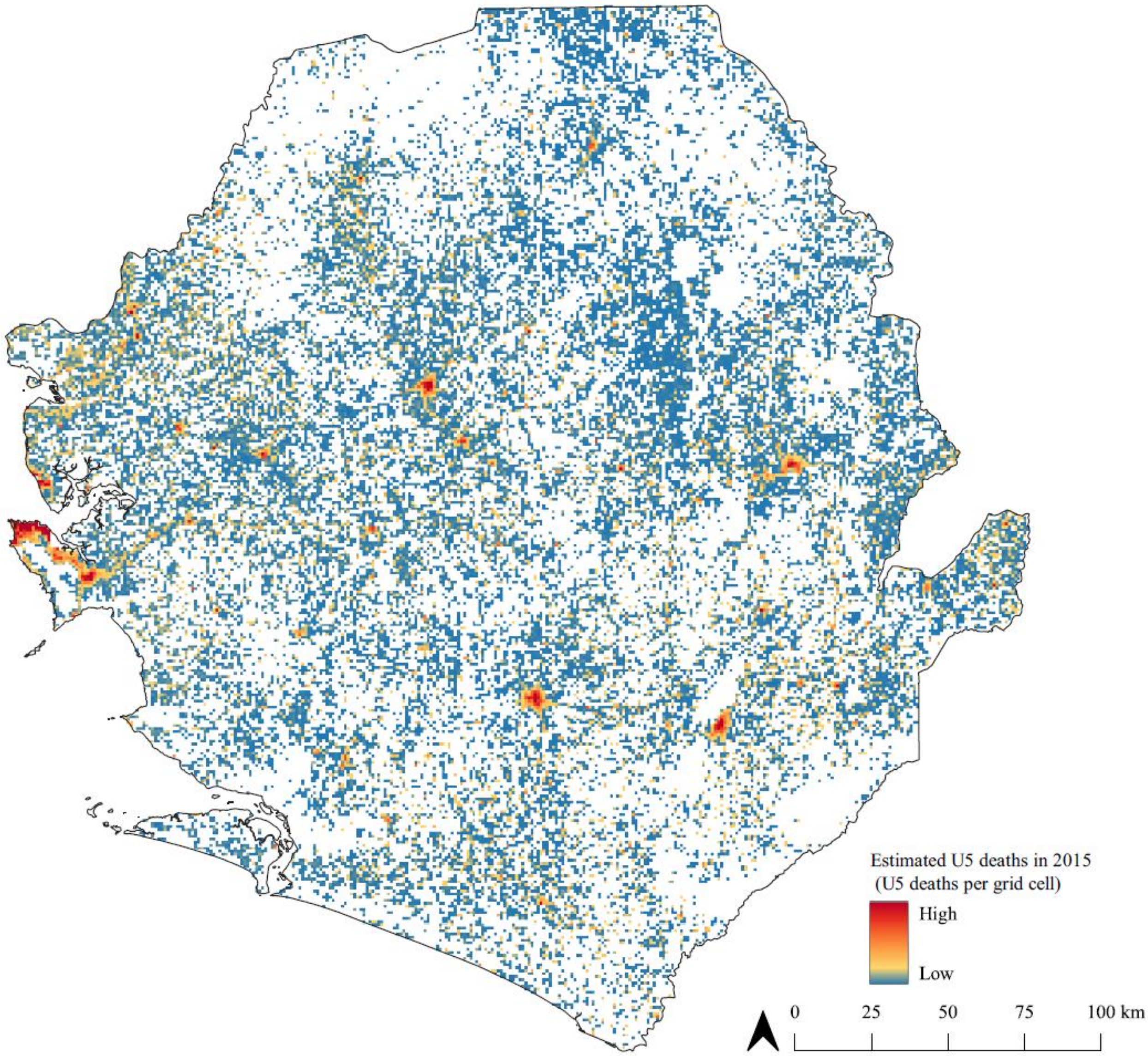
Supplementary Figure 29. Estimated population count in easy to reach (ETR) areas in 2015 per grid cell at 1km x 1km resolution.

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.

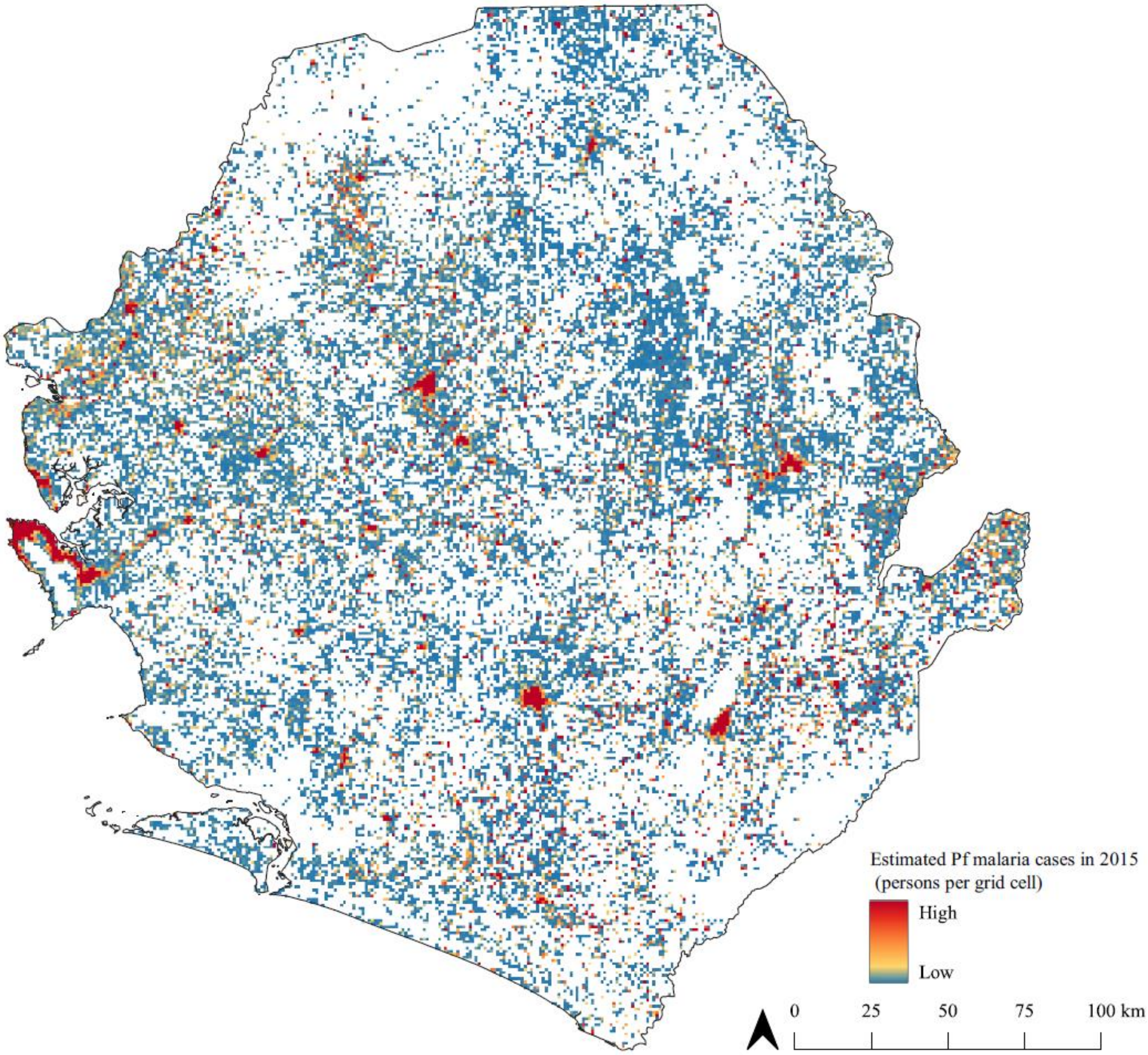


Supplementary Figure 30. Estimated population count in easy to reach (HTR) areas in 2015 per grid cell at 1km x 1km resolution.

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.[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.

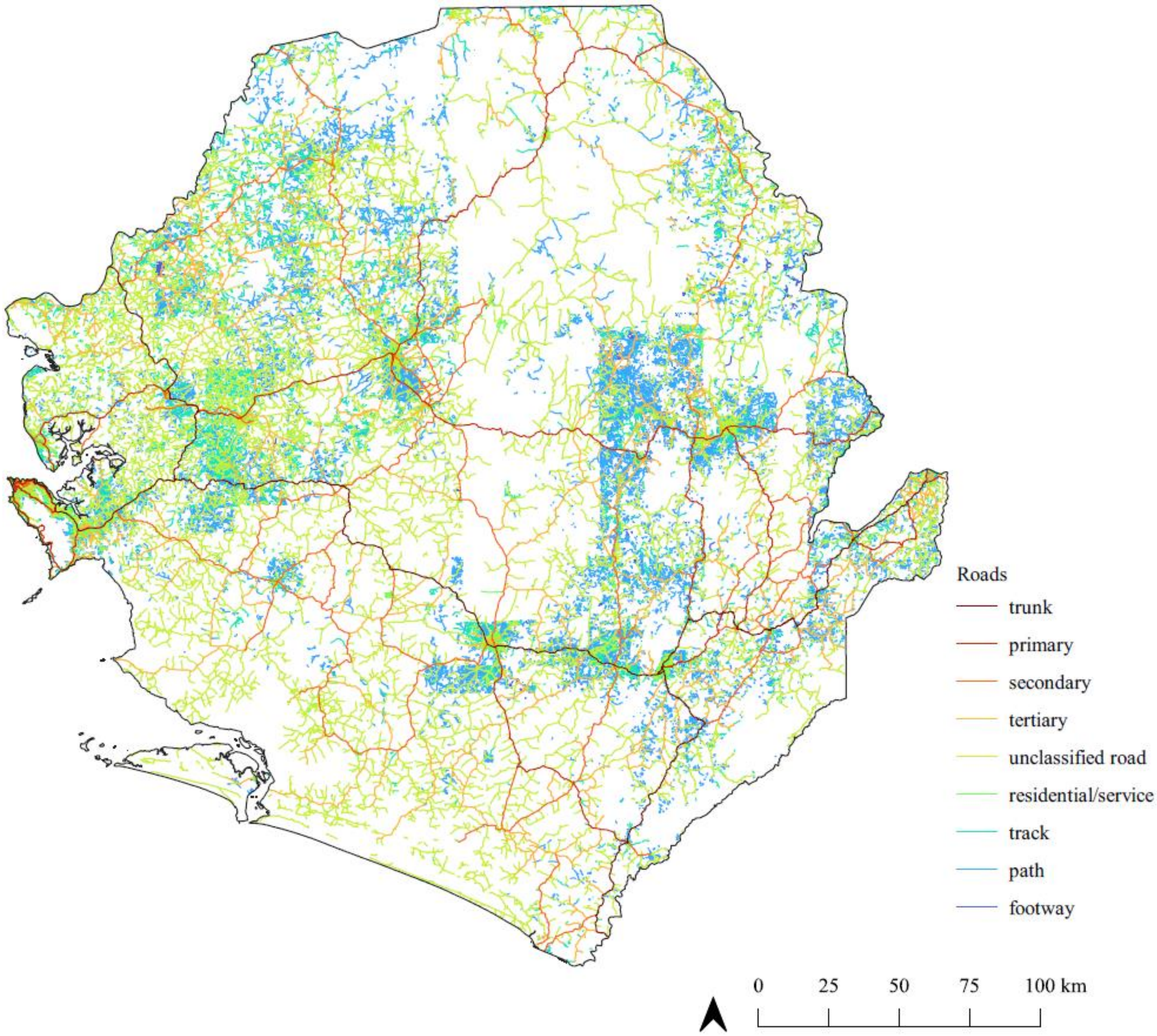


Supplementary Figure 31. Mean count of U5 deaths in 2015 per grid cell at 1km x 1km.
Mean count of U5 deaths in 2015 at 1km x 1km derived from the mean U5 mortality rate in 2015 (IHME[3]) at 5km x 5km, resampled to 1kmx1km and multiplied by the infant population in 2015 (Worldpop[2]) at 1km x 1km

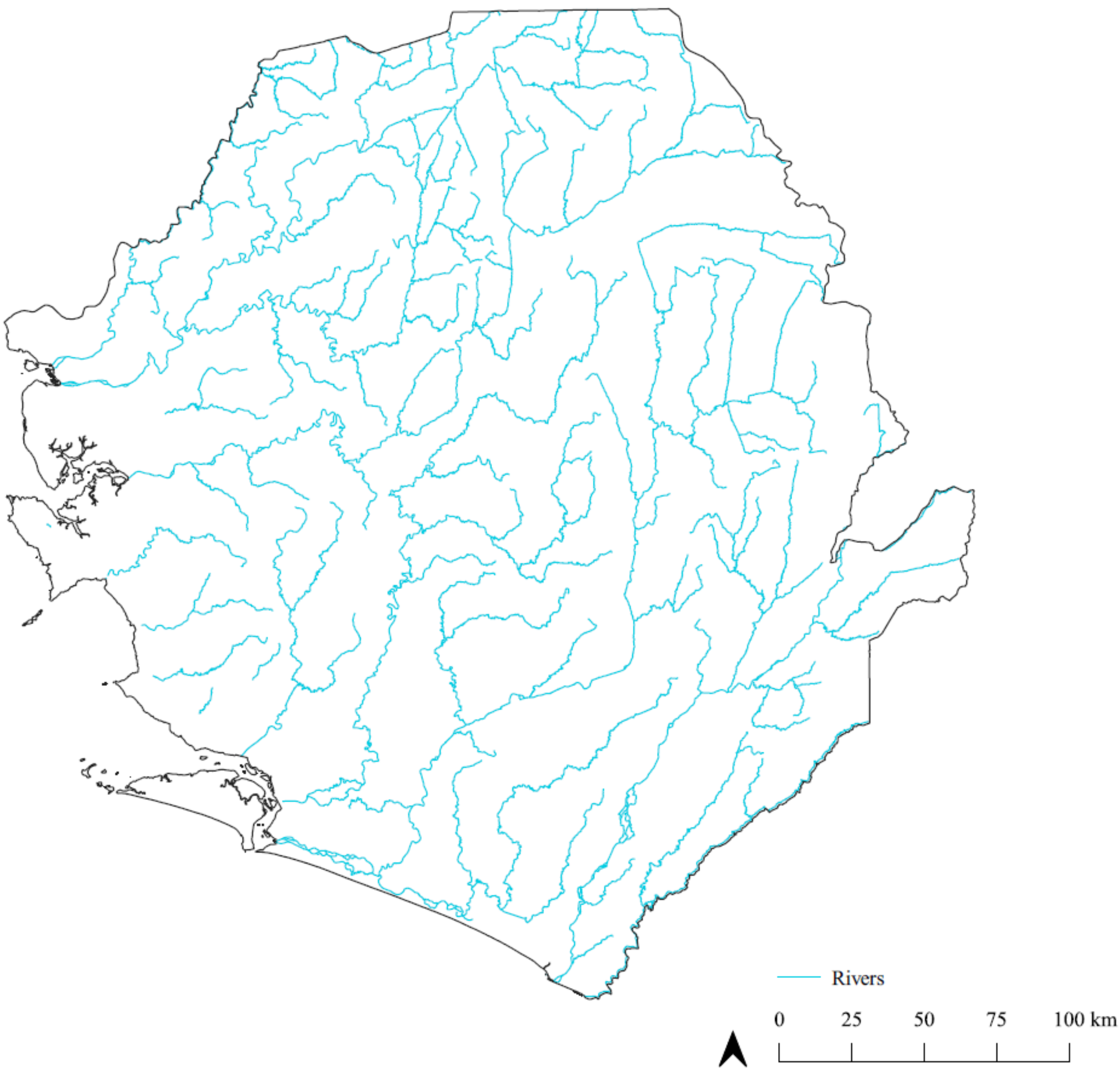


Supplementary Figure 32. Estimated *Pf* malaria cases among all ages (0-99 years) in 2015 per grid cell at 1km x 1km resolution.

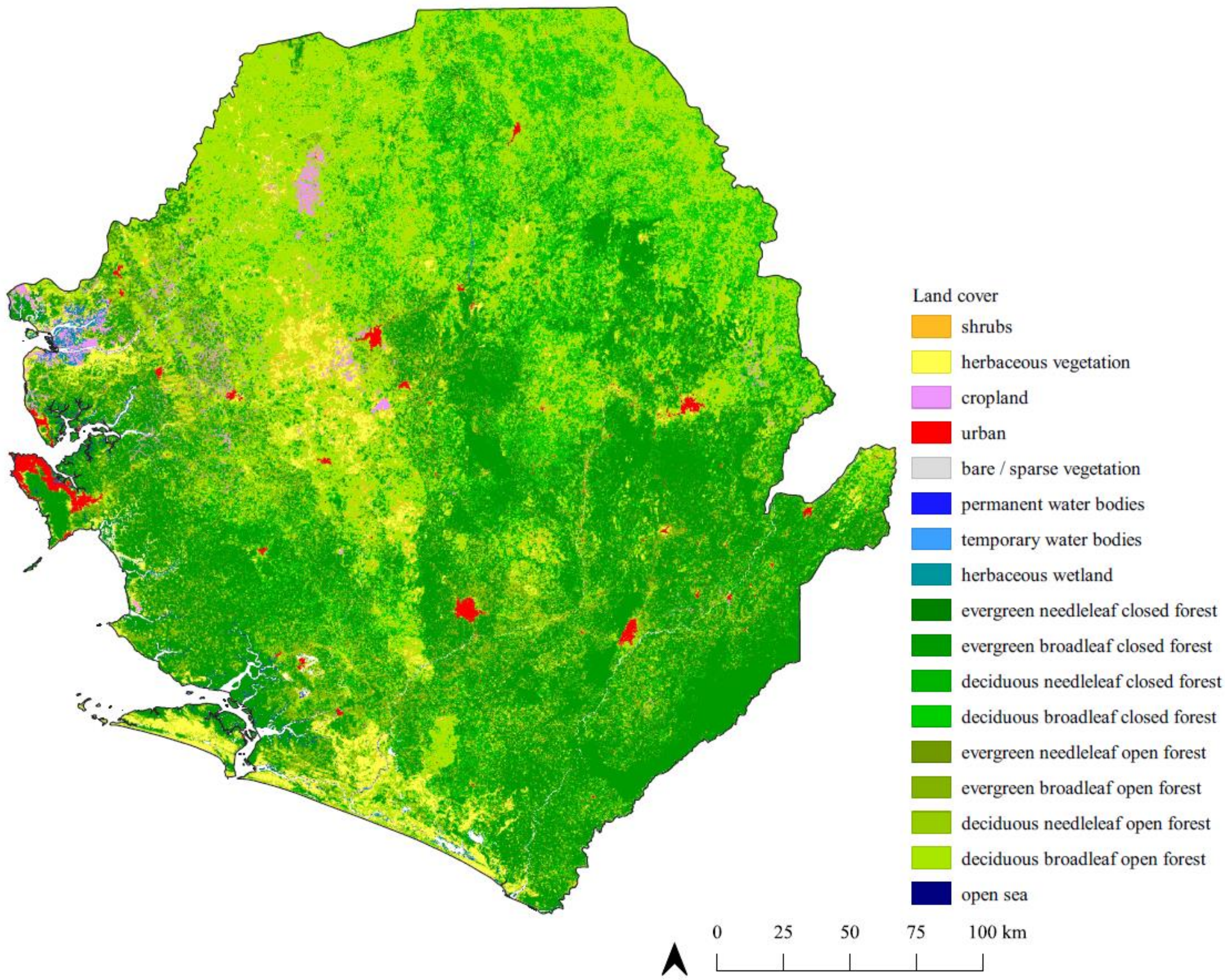
Annual mean incidence of Plasmodium falciparum (Pf) malaria among all ages (0-99 years) in 2015 globally at 2.5 arcminutes (approximately 5km x 5km) resolution from Weiss et al 2019[4], reprojected to 1km x 1km resolution and multiplied by the estimated population in 2015[2] (see Methods).



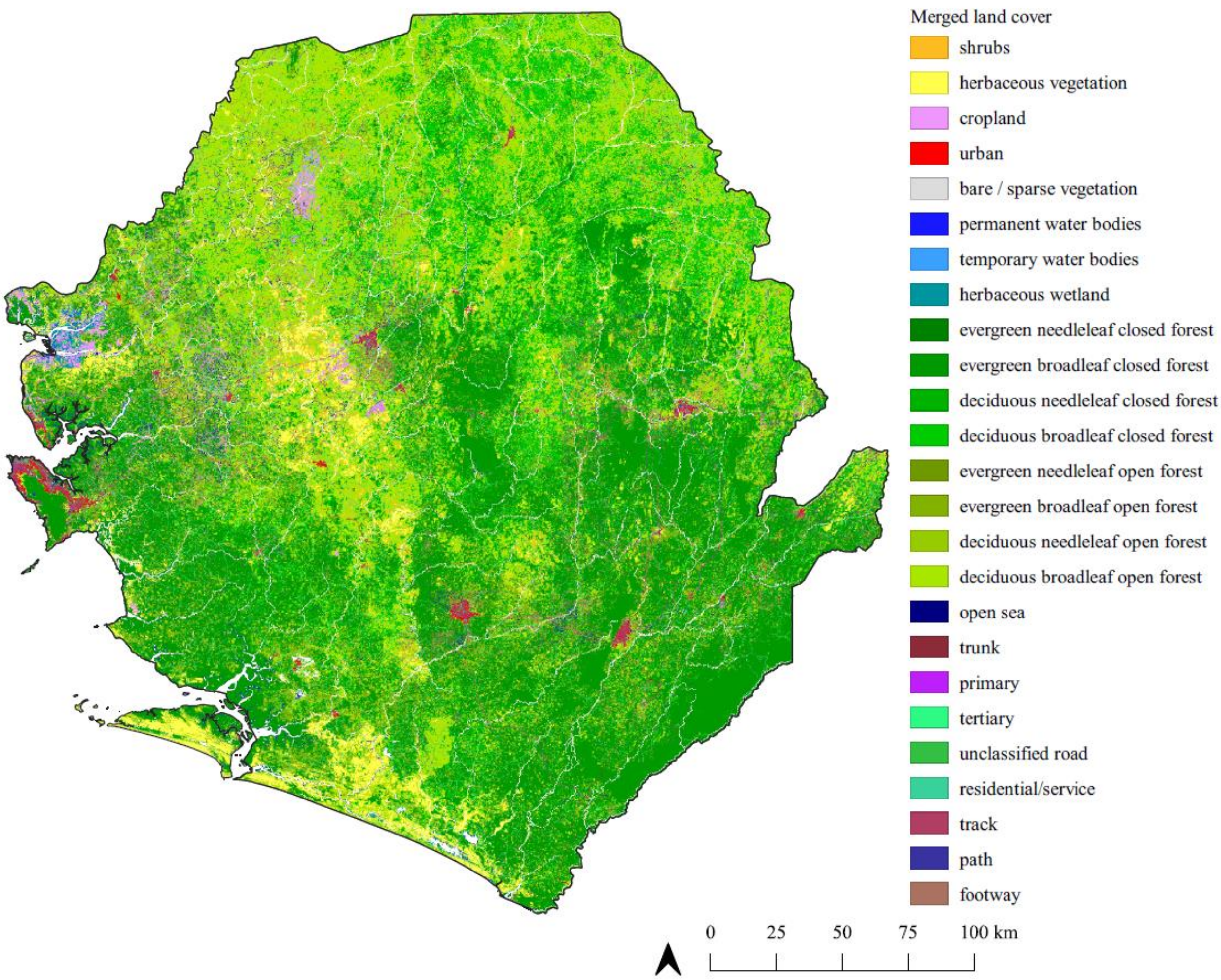
Supplementary Figure 33. Road network
HOTOSM Sierra Leone Roads (OpenStreeMapExport)[5]



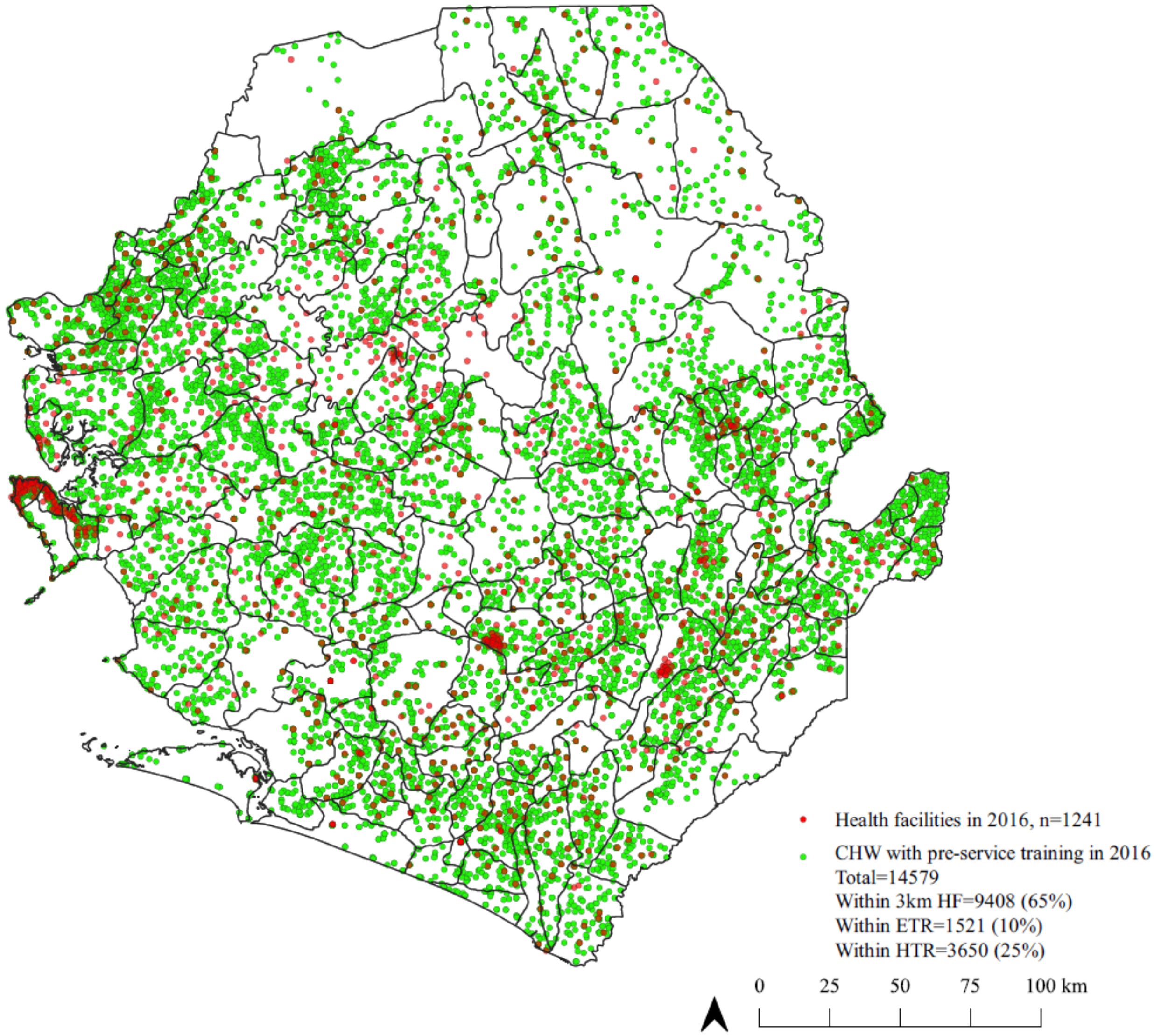
Supplementary Figure 34. Rivers. HOTOSM Sierra Leone Waterways (OpenStreetMap Export)[6]. Note: only includes "main" rivers and "major rivers".



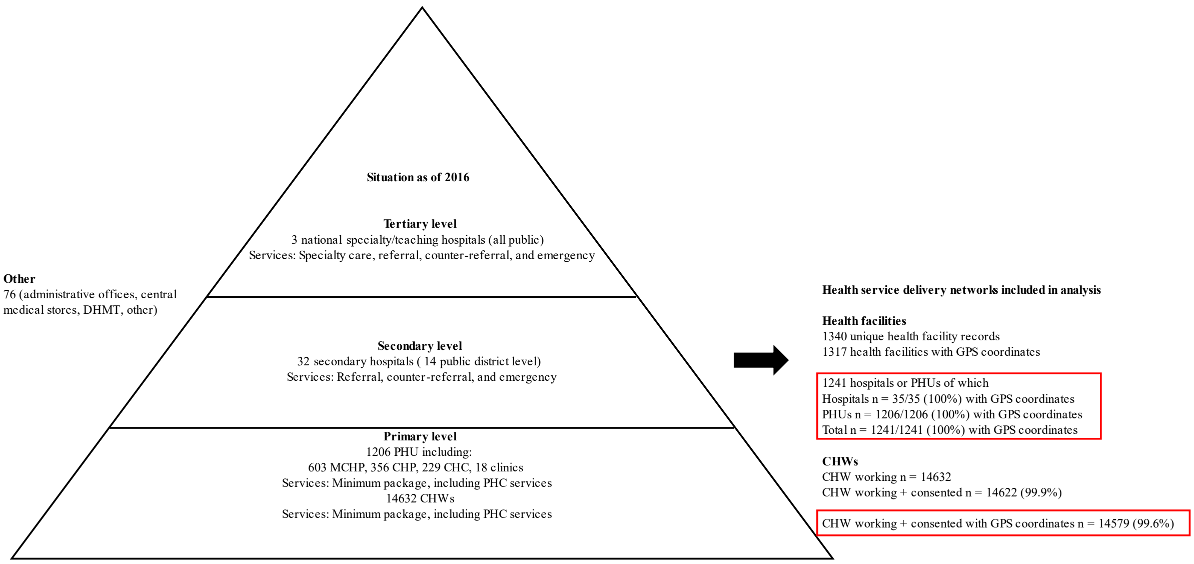
Supplementary Figure 35. Land cover at 100m x 100m resolution. Land cover at 100m x 100m and 1km x 1km resolutions (latter not shown). Discreet land cover classes are based on the UN Land Cover Classification System (LCCS)[7]



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[8]



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[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.

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.[11] 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.[12]

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.[13] 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 sise 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) aides 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] 2016[17] and, more recently in 2021.[18]

The following summarises points from the CHW policy of 2012[16] 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".[18] 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)[9] 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.[12] 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.[14]

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[10] 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.[12] 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.[12]
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[8], 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.[12]

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.[12]
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.[12]
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.[12]

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 2015in 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 Zürich[12] 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 Zürich[12] and the process described above (see the GeoTIFF file “raster_dem_dem” in Supplementary Appendix 1c at https://doi.org/10.5281/zenodo.5712134).

Land cover

We obtained a GeoTIFF raster for land cover in Africa [c_gls_LC100-LCCS_201501010000_AFRI_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[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 x1km resolution (geographic coverage, efficiency, and scale-up analysis) we prepared a GeoTIFF land cover raster at 1km x 1km resolution using the GDAL "warp" tool in QGIS 3.18.2 Zürich[12] 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[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.5712134).

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_sierra_leone_roads.[5] 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[12] (see file v_SLE_v1_roads_100m.shp in Supplementary Appendix 1c at https://doi.org/10.5281/zenodo.5712134). 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[8] project at 100m x 100m resolution and used the merge land cover tool in Accessmod 5.6.56[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[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_sierra_leone_waterways.[6] 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[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.5712134). 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[8] project at 100m x 100m resolution and used the merge land cover tool in Accessmod 5.6.56[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[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[8] (see file "raster_land_cover_merged_r_SLE_land_merged_final_100m.tif" in Supplementary Appendix 1c at https://doi.org/10.5281/zenodo.5712134). The process is described in detail in Ray et al, 2008.[10] 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[8] project at 1km x 1km resolution (see the file "raster_occupation_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.5712134). 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.[19,20,8] 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.[2] The 2015 Worldpop layer v2.0 was developed following the Random Forest (RF)[21] – based dasymetric mapping approach[22] and building footprints[23] and adjusted to 2015 disaggregated census data.[23] 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[12] 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[12] 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[12] 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[12] 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[12] [r_SLE_ratPop15OtN_100m] 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,[12] we multiplied the rasterised ratio [r_SLE_ratPop15OtN_100m] by the Worldpop population in 2015 at 100m x 100m resolution [SLE_population_v2_0_gridded_reprojected_unadjusted] 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[8] 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.5712134).

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.5712134.

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 x100m 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 Zürich[12] 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 Zürich[12] 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 SLE v.2.0, resulting in a reprojected raster for the population count in 2000 constrained to the footprint of the 2015 Worldpop SLE v.2.0. [sle_ppp_2000_UNadj_reprojected_100m], effectively
2. We used the "Zonal statistics" tool in QGIS 3.18.2 Zürich[12] 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 SLE v.2.0.
4. We rasterised this ratio at 100m resolution using the "Rasterise" tool in QGIS 3.18.2 Zürich[12] 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 Zürich[12] 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.5712134):

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 for 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.[25] 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[12] 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[12] 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[12], with the extent of the estimated total population raster for 2015 at 1km x 1km [raster_population_r_SLE_pop15F_1km].
4. We ran a Zonal Statistics in QGIS 3.18.2 Zürich[12] for the reprojected raster for children under one year of age in 2015 constrained to the footprint of the 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[12] 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[12] 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 raster of the estimated population in 2015 [raster_population_r_SLE_popU1F_1km]. See supplementary Appendix 1c at https://doi.org/10.5281/zenodo.5712134).

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_U5M_2000_2017_Q_UNDER5_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),[2,28] accessed on 8 October 2020, at http://ghdx.healthdata.org/lbd-data.
2. We used Raster Calculator in QGIS 3.18.2 Zürich[12] 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[12], 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_U5M_2000_2017_Q_UNDER5_MEAN_Y2019M10D16_2015_reprojected_1km].
4. We used Raster Calculator in QGIS 3.18.2 Zürich[12] 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

(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 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[12] 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.5712134).

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/.
2. Using the GDAL Warp tool in in QGIS 3.18.2 Zürich[12], 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[12] 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[12] 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.5712134).

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.

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 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.[8] 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[29] and they are clinically relevant (e.g., for prompt treatment of severe illness).[30] 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[8] 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.[8]
    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_wvd_100m
   c. walking to the nearest road, then using motorised transportation in dry conditions: raster_travel_time_r_SLE_ga_facilities_wvw_100m
   (see Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.5712134).
3. We used the "Zonal statistics" tool within Accessmod 5.6.56[8] 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.5712134. 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.[10] We used the "geographic coverage" module of AccessMod 5.6.56[8] 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 policy[18] – 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 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.5712134 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.[18] 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 sise (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.5712134 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 sise (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 sise, 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.5712134 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 sise (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_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 sise (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-Bucareşti[13] 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 sise, 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.5712134 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 sise (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 sise (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-Bucareşti[13] 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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