Malaria elimination: moving forward with spatial decision support systems

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Operational challenges facing contemporary malaria elimination have distinct geospatial elements including the need for high-resolution location-based surveillance, targeted prevention and response interventions, and effective delivery of essential services at optimum levels of coverage. Although mapping and geographical reconnaissance (GR) has traditionally played an important role in supporting malaria control and eradication, its full potential as an applied health systems tool has not yet been fully realised. As accessibility to global positioning system (GPS), geographic information system (GIS) and mobile computing technology increases, the role of an integrated spatial decision support system (SDSS) framework for supporting the increased operational demands of malaria elimination requires further exploration, validation and application; particularly in the context of resource-poor settings.

Operational challenges facing malaria elimination from a geospatial perspective

Malaria elimination is back on the global health agenda [1–3]. Current global strategies for the elimination and eventual eradication of malaria are outlined in the Roll Back Malaria (RBM) Global Malaria Action Plan (GMAP) and include: (i) the scaling-up and sustainment of intensive malaria control operations; (ii) progressively eliminating malaria from the endemic margins inward (i.e. shrinking the malaria map); and (iii) the continuation of research into new tools and approaches to malaria control and elimination [4,5].

To support effective implementation of the GMAP, robust health systems are essential in each endemic setting because this ensures the effective delivery of scaled-up malaria services and interventions at optimum levels of coverage in target areas [6,7]. As malaria programmes enter pre-elimination and progress forward, detailed and responsive surveillance also becomes a central component to any supporting health system [6,8]. To support the transition from control to elimination the need for improved data and an ability to generate additional information, knowledge and evidence from such data are prerequisites [9]. This often presents significant challenges to existing national health information systems (HISs) in malaria endemic countries [10,11].

The heterogeneous nature of malaria transmission and microepidemiological variability between target areas have long been acknowledged as being important problems for planning appropriate interventions [12,13]. For elimination, programmes must have an ability to effectively and swiftly identify, locate and eliminate transmission, mostly through a monitoring and surveillance strategy of routinely reported passive case data and targeted active case detection [14]. Even more importantly, contemporary elimination programmes also require robust surveillance–response mechanisms to effectively locate and eliminate all infection reservoirs, manage transmission hotspots/pockets, as well as identify and treat imported infections before local transmission reoccurs [14]. These operational priorities, coupled with the explicit spatial nature of malaria itself, highlight the importance of geography and locale across all aspects of malaria elimination management and stress the relevance of incorporating a spatial component into any accompanying HIS.

The significance of mapping as a powerful epidemiological tool has been recognised right from the foundations of epidemiology, when John Snow’s famous maps were published relating the location of cholera cases to the Broad Street water pump [15]. Current mapping approaches have largely focused on illustrating, modelling and predicting the distribution or patterns of disease and disease risk. However, comparatively less research has been conducted on how best to utilise and apply geospatial technology to actively support the priorities and increased demands of malaria elimination at an operational level, particularly in the context of resource-poor and capacity-limited settings. The aim of this paper is to provide an overview of GIS and mapping as an operational tool for malaria management; and highlight the potential expanded role of GIS-based SDSSs in guiding and meeting the scaled-up operational demands of current day malaria elimination programmes.

Contemporary malaria mapping approaches using geographical information systems

With the introduction and expansion of GIS today, the role of mapping in malaria control and elimination has grown. Malaria incidence or prevalence mapping is the most basic contemporary application and is primarily used to visualise and identify trends and patterns in the spatial...
distribution of malaria over defined geographical areas [16,17]. Mapping and geostatistical applications are used to identify relationships between the spatial distribution of malaria and other variables such as weather and climate [18–23], land use and demography [24], and vector breeding sites [25,26]. Mapping of malaria risk is also now a prominent form of contemporary mapping that utilises spatial data and imagery from a variety of remote sources such as satellite imagery, aerial photography and radar. Remote sensing (RS) data have been used widely for the identification, characterisation, monitoring and surveillance of breeding habitats, and mapping of malaria risk [27–32].

Advanced GIS-based spatial analysis techniques have also been adopted to identify, predict and map malaria risk at a variety of different scales. On a global scale, the distribution of Plasmodium falciparum endemicity has been mapped from parasitological data using robust geostatistical modelling frameworks [33,34]. Similar spatial statistical models have also been produced to explore and predict malaria risk at regional, national and local levels [32,35–43]. From a malaria elimination perspective, predictive maps provide essential tools to illustrate malaria risk and its distribution across a variety of scales (i.e. globally, nationally and subnationally), highlight favourable areas for elimination, and strategically target priority interventions towards relevant foci within designated elimination zones.

Map-based graphical interfaces are also being integrated into modern reporting applications. For example, mobile phone short message service (SMS) technology has been utilised in Africa to strengthen the routine reporting of antimalarial drug supplies at health facilities [44,45]. Coupled with the standard tabular reporting functionality, data from health facilities sent via SMS are also automatically updated onto web-based map interfaces to visualise the real-time supply and spatial distribution of antimalarials within target areas, providing a mechanism to support drug supply management and the timely detection of stockouts at the health facility level [44,45].

At a programme implementation level, GIS technology is still only playing a limited role in supporting direct operational priorities of malaria elimination within designated target areas. Until recently, little research has explored the application of geospatial information and GIS technology for malaria elimination operations, and in many cases a lack of data at a high enough resolution to support elimination activities has been a limiting factor [46].

Geographical reconnaissance: an operational tool for malaria elimination

Historically, the lack of access to spatial data and operational tools often represented a significant barrier in control operations [47]. Despite these traditional limitations, mapping has long played an important operational role in malaria control and eradication. GR has been used in malaria programmes to identify and map target areas and enumerate populations for the coordination, implementation and quality control of field operations such as indoor residual spraying (IRS) and mosquito net distribution. GR involves data collection, mapping and sampling procedures to determine the number, location and accessibility of settlements within intervention target areas. Operationally, it provides a basis for the selection of field centres and depots, for designing schedules and itineraries, planning deployment of transport and assessing the completion of planned activities [48]. GR can also be used to define as accurately as possible the geographical limits of malaria epidemics and transmission foci, and assess epidemic potential [49,50].

During the global malaria eradication period (GMEP) of the 1950s to the 1960s, GR involved conducting detailed paper-based censuses and surveys of all households within target areas, sampling and measuring selected building structures and developing sketch maps of settlements using compass and pacing techniques [48,51]. Figure 1a provides an example GR household locality sketch map produced during the GMEP era. A major limitation of traditional GR has often been the time-consuming, inaccurate and resource-intensive processes associated with fieldwork and paper-based sketch-mapping. Therefore, traditional approaches to GR are now often omitted from current day malaria programmes due to these inefficiencies.

During the GMEP, interventions were often carried out independently from existing health systems because they were considered inadequate to support the largely vertically organised malaria eradication programmes [6]. Because technology at the time did not exist to integrate paper-based GR data into existing health systems, GR data generally had poor geographical coverage and were not suited to surveillance [14,52]. However, recent advancements in handheld mobile technologies, such as personal digital assistant (PDA) devices, tablet computing, smartphones and integrated GPSs, now present significant opportunities to expand the coverage and application of field-based GR. Handheld technologies available today can support the rapid collection and subsequent immediate mapping of data at a high resolution (e.g. the household level), providing a cost-effective, efficient and accurate approach to geospatial field-based data collection [53–56].

If consolidated effectively within a GIS, high-resolution GR and micromapping data, particularly at a sub-settlement level (e.g. household, community or similar), can provide a detailed georeferenced dataset to support key operational priorities of elimination such as the implementation, monitoring and evaluation of targeted vector control interventions and surveillance [57]. Recent GR activities carried out in designated elimination provinces in the Solomon Islands and Vanuatu have adopted such a standardised approach to rapid GR and micromapping, utilising handheld PDA, GPS and GIS technology to develop a georeferenced database of households within target elimination zones [57]. Through a GIS-based SDSS, this dataset has been used to guide priority elimination interventions such as focal IRS and universal long-lasting insecticidal net (LLIN) distribution to ensure maximum and uniform levels of coverage are achieved in the designated target areas [58]. Figure 1b provides an example LLIN coverage map automatically produced within the SDSS based on household GR data to support scaled-up
malaria elimination interventions in the Solomon Islands. As the intensive control and progressive elimination programmes in the Solomon Islands and Vanuatu continue to evolve, this framework is anticipated to provide a location-based platform to support additional operational priorities including passive and targeted active case detection, surveillance and response.

**From a spatial decision support system to malaria elimination**

A SDSS provides computerised support for decision making where there is a geographic or spatial component to a decision [59]. These are generally based around a GIS that integrates database management systems with analytical models, graphical map display and tabular reporting capabilities, and the expert knowledge of decision makers [59,60]. A SDSS provides a mechanism to link routinely collected data with associated geographic locations, conduct spatial queries and analysis, and produce automated reports and illustrative maps for relevant areas of interest. These systems, when designed and applied effectively, have the potential to provide health programmes with a powerful and user friendly operational tool for evidence-based decision making to support management issues with a spatial or geographical focus. Figure 2 illustrates a conceptual SDSS framework for malaria elimination. Key elements of a SDSS include: (i) data inputs from a variety of sources (including geospatial data layers); (ii) automated outputs to guide informed and strategic decision making for designated applications; (iii) application intervention outcomes re-entered back into the SDSS as a cyclical input; and importantly (iv), expert knowledge, integrated throughout all stages of the SDSS process. Although only limited research has been conducted on the operational applications of SDSS for malaria elimination, elements of SDSS design have been implemented in several vector-borne disease control programmes to date (Box 1). A detailed overview of the current role of SDSS in supporting the progressive malaria elimination programmes in the Solomon Islands and Vanuatu is also presented in Box 2.

**The transition from control to elimination**

As countries pursue GMAP [5] and progressively shift from malaria control to pre-elimination, elimination and the eventual prevention of reintroduction of malaria, respective programmes must not only meet the scaled-up operational priorities of these individual phases but also have

![Figure 1. GR mapping: traditional processes versus new technology. (a) An example of a hand-drawn GR household locality map produced during the GMEP using traditional field-based sketching methods to support IRS interventions (circa 1961–1962) [48]. (b) An example of a LLIN household distribution coverage map automatically generated in a SDSS, Temotu Province, Solomon Islands (2011). Household location data collected during baseline GR operations using digital handheld computer and GPS technology is stored in a SDSS and used to support the planning, implementation and assessment of priority elimination interventions such as LLIN distribution and focal IRS, and positive case surveillance at a household level as part of the progressive Solomon Islands Malaria Elimination Programme.](image-url)
the ability to effectively measure and assess progress to support the strategic transition between phases. A standardised approach to stratifying both malaria risk and incidence, as well as the overall preparedness of malaria programmes to implement elimination, can be developed within a GIS-based SDSS to visualise (at differing administrative and geographical scales) and delineate target areas, and to measure and assess progress made within

**Box 1. Example of SDSS applications in malaria and vector-borne disease management**

A GIS-based malaria case surveillance system has been trialled by the Mpumalanga Malaria Control Programme in South Africa. Malaria cases were georeferenced at town and village level and maps of malaria incidence generated [64]. These maps illustrated spatial heterogeneity of malaria risk that had previously been concealed in table-based summary data on incidence, and were used to enhance decision making through the identification of priority areas and efficient allocation of limited resources to support spraying interventions in these locations [64]. Similarly, a GIS-based DSS has been developed in Dindigul, Tamil Nadu, India to guide control interventions. A significant benefit of this SDSS was that it enabled real-time monitoring via a graphical map interface of mosquito larval densities, malaria cases and community awareness programmes [65]. Surveillance carried out using the SDSS enabled programme managers to identify localised clusters of malaria transmission and to rapidly associate probable cause, specific vectors and probable human source, so that appropriate preventative actions could be carried out [65].

A computerised management system with a SDSS component has been implemented in southern Mozambique to monitor vector control spraying operations [66]. The number of structures sprayed was digitally recorded, insecticide spray application rates calculated and coverage by a spray team mapped over a large geographical area (approximately 220 000 structures, covering an area of 13 770 km²) [66]. This SDSS provided programme managers with an effective operational tool to actively monitor resource usage and spray progress, identify problems at the level of an individual spray operator, and implement remedial action when required to assure high coverage and programme efficiency [66].

Following the success of stand-alone DSS in malarious provinces of South Africa, an integrated Malaria Information System (MIS) has been developed and implemented in this region to facilitate pragmatic decision making [67,68]. Maps generated from the GIS-based MIS can be produced at a variety of administrative levels ranging from national to village level and have played an important role in formulating malaria insecticide and drug policies, providing appropriate information for tourists, evaluating changes in malaria transmission over time and allocating resources to control malaria [67].

SDSS applications have also been implemented in other vector-borne disease control programmes, such as for dengue. In Thailand, vector populations and dengue cases have been mapped within a SDSS framework and used to monitor dengue outbreaks [69]. Similarly, a SDSS has been implemented in Singapore to identify, map and monitor dengue ‘hotspots’ [70]. Dengue vector surveillance in Singapore is also carried out using GIS, integrating data from an island-wide monitoring network of 2000 ovitraps [71]. Vector breeding data collected using the ovitraps are analysed weekly to identify hotspots and risk areas, and results used to guide control operations [71]. A dengue SDSS has been implemented in Mexico utilising Google Earth™ and other free software such as the WHO Health-Mapper, highlighting the opportunities to strengthen overall public health capacity and facilitate SDSS approaches to the prevention and control of vector-borne diseases in resource-poor environments [63].
Progressive malaria elimination programmes are currently implemented in Temotu and Isabel Provinces, Solomon Islands and Tafea Province, Vanuatu. Key challenges faced in all three provinces are characterised by those typical of remote Melanesian communities and include limited infrastructure, access and human resource capacity. As a means to support the increased operational demands of elimination and to ensure the effective targeting and delivery of interventions and essential services is achieved, particularly in the context of the local challenges, a SDSS framework has been adopted (Figure 2).

As part of the transition from control to elimination, universal household LLIN distribution and focal IRS interventions were nominated as key frontline strategies. Routine malaria data and entomological surveys [72], as well as malaria risks maps in Tafea [43], were used to identify focal IRS areas. GR using integrated PDA and GPS was carried out by provincial vector-borne diseases control programme (VBDCP) personnel to map households and collect baseline information required to support key interventions [57]. A total of 20,485 households and a population of 90,292 were recorded during GR operations, with an average of 42.5 households and population of 180 recorded per PDA/GPS unit per day. As part of daily GR procedures automated data backup and manual data verifications procedures were also conducted.

GR household data have formed an integral baseline component of the SDSS approach to support elimination. Both geographical map-based and tabular data outputs were utilised to support all facets of managing and assessing priority interventions such as LLIN distribution, entomological surveillance and focal IRS [58]. Figure 3 provides an example screenshot of the Isabel Province SDSS graphical user interface, illustrating the map-based and tabular components of the system. SDSS applications being developed in the Solomon Islands and Vanuatu are now currently focusing on guiding geospatial case surveillance response as each respective programme prepares to move towards the latter stages of elimination.

Individual SDSS frameworks have been developed at each provincial level and are primarily operated by provincial VBDCP officers. A key development focus is the customisation of individual provincial SDSSs to support the specific needs, existing systems and software, and current elimination position of each respective province. Hardware used includes standard laptop computers for SDSS operation and integrated PDA/GPS for field activities. Microsoft Access (Microsoft Corporation, Redmond, WA, USA) and MapInfo Professional (Pitney Bowes Software Inc., Troy, NY, USA) software are used as the SDSS platform.

As illustrated in Figure 2, expert knowledge is an integral component of a SDSS framework. To ensure operational capacity exists at each provincial level, field-based training is conducted before the implementation of any additional SDSS application. Collaboration and continuous communication is also prioritised, with a Pacific Malaria Elimination Surveillance, Monitoring and Evaluation (SM&E) Technical Working Group providing a forum for Solomon Islands and Vanuatu national and provincial VBDCP SM&E personnel, and external technical partners, to exchange ideas, access remote support and discuss SDSS issues.

Supporting the operational priorities of elimination
As indicated in Figure 2, an integrated SDSS also provides the potential to directly support several operational priorities of malaria elimination including: (i) routine reporting, monitoring and evaluation; (ii) vector control and malaria prevention interventions; and (iii) case management and surveillance response. The ability to merge traditional field-based mapping principles such as GR with GIS and database technology within a SDSS creates an effective platform for increased user access and functionality of spatial data to support decision-making processes (Figure 3). A SDSS framework can create an opportunity to integrate and relate traditional elements of malaria management with geospatial data, potentially empowering local malaria personnel at an operational level with necessary tools to support the geographical focus required for the successful implementation of key interventions within an elimination context. Similarly, the ability to integrate map-based functionality into an elimination-focused health system could provide a powerful visual mechanism to monitor the distribution of essential malaria services (such as antimalarial drug supplies) and support the early detection of potential disruptions to their effective delivery, as well as provide an evidence-based tool to support effective decision making and guide appropriate response actions as required.

Surveillance response and prevention of reintroduction
National programmes progressing with malaria elimination must have the capacity to reorient themselves to further emphasise surveillance, reporting and information systems [5]. As the numbers of positive cases in target areas fall and elimination priorities also shift towards prevention of reintroduction, national programmes will require rigorous evidence-based surveillance strategies and approaches to ensure (and report) that key elimination interventions have effectively interrupted transmission over a sustained period of time. The geographical nature and spatial variability of malaria lends itself well to elements of GIS and map-based monitoring tools. Scope currently exists to further develop and strengthen SDSS-based principles for malaria elimination to support: (i) the detailed surveillance of passively reported cases via a map-based interface to view the respective spatial–temporal distribution of individual malaria cases; (ii) individual malaria case investigation and follow-up; and (iii) the development of surveillance response mechanisms to strategically guide active case detection activities based on the spatial distribution of passive case data to detect, locate and halt local transmission, and prevent reintroduction in designated elimination zones.

Technical and operational capacity
As described in Box 2, SDSS design should focus on addressing the specific needs of an individual programme and aim to incorporate and build upon existing systems
and software in place. Access to GIS software has been a significant obstacle in the past, with the cost of proprietary software often a limiting factor for health programmes with limited resources. However, with the increasing availability of free open source GIS software, open-access GIS data and web-based mapping alternatives (e.g. Quantum GIS, OpenStreetMap and OpenLayers), it is expected that access to these resources will steadily improve [61–63].

Local knowledge is an essential component of any decision support application for managing malaria interventions [8]. As suggested in Figure 3, expert knowledge is central to an effective SDSS framework. In the context of malaria elimination, the expert knowledge of local programme personnel is paramount to the effective implementation and delivery of any intervention or service. As such, SDSS design must be targeted, developed and implemented at the local level. As outlined in Box 2, emphasis should be placed on building SDSS operational capacity of local elimination officers through a combination of field-based training and continuous remote support. Access to continuous remote support through the establishment of forums such as technical working groups and web-based discussion boards is imperative to ensure operational capacity is sustained at the appropriate levels. Given current improvements in free web-based communication technology such as voice-over-Internet Protocol (VoIP) services and collaborative websites (e.g. internet forums and wikis), remote support options present a feasible, effective and cost-effective approach for sustaining operational capacity, particularly in remote settings.

Current limitations and future research
Limited research has been conducted to quantify the benefits of SDSS as a decision-support tool for malaria elimination, or to explore the limitations of the SDSS approach. Challenges faced by malaria programmes regarding GIS have included information technology concerns such as hardware, software and training; availability of adequate and reliable GIS data; and the accessibility of appropriate (and user friendly) GIS methodologies [16]. As mentioned, the increasing open-source market is likely to provide increased access to GIS software and baseline GIS data. GR using GPS and handheld digital devices also provides an effective field method for the rapid and accurate collection of relevant georeferenced data. SDSS user acceptability surveys have also been conducted in the Pacific, indicating strong support for SDSS methods for guiding the operational priorities of malaria control and elimination [57,58].

The small number of SDSS users and systems currently in place suggests a need for further research and broader application of SDSS to validate the integrity and robustness of these systems, particularly in resource- and
capacity-limited settings. A significant challenge for the successful implementation of SDSS will be to ensure operational capacity at the programme implementation level is sustained. The delivery of appropriate and practical training at this level is essential. Additionally, novel approaches to providing remote operational support to malaria programmes should also be explored. Further investigations should also focus on analysing the costs associated with the development and implementation of a SDSS tool to support the increased operational demands of intensified control and elimination versus traditional approaches to malaria intervention management.

Concluding remarks
Malaria risk is characterised by spatial variability, manifested by clustered patterns of malaria cases. As such, the effective management of malaria requires a spatial perspective and the inclusion of a geographical component to any malaria elimination information system. Maps provide effective monitoring, evaluation and surveillance tools to overcome the complexities associated with the spatial variability of malaria. Although this concept is not new, the increasing scale and demands of contemporary malaria elimination and intensified control call for new approaches to old practices, particularly in the context of mapping and its potential to strengthen existing health systems. Modern advancements in GIS and location-based data collection technology create opportunities to establish geospatial components into information systems, thereby strengthening the ability of the systems to support the scaled-up operational priorities of malaria elimination. Further research should be directed at exploring the opportunities SDSS approaches have in both targeting priority operational areas and ensuring the effective delivery of priority health services and interventions at maximum and uniform levels of coverage within these target areas. If adapted effectively, integrating map-based technology and HISs into a SDSS framework will provide decision makers with a unique and practical tool to support all key facets of malaria elimination operations management including the planning, implementation, monitoring and evaluation of key interventions. Similarly, a SDSS also provides an effective mechanism to support location-based surveillance and guide appropriate targeted responses measures. Consequently, the role of SDSS merits urgent further development, validation and larger-scale application as malaria programmes continue to progress along GMAP towards the overall goal of elimination and eventual eradication.

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