RESEARCH ARTICLE

Estimating malaria disease burden in the Asia-Pacific [version 1; peer review: 2 approved with reservations]

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Abstract

Background: The Asia-Pacific aims to eliminate malaria by 2030. Many of the 22 endemic countries have earlier targets. To track progress towards elimination and predict timelines and funding required it is essential to have an accurate picture of the true burden of malaria over time. Estimating this is a major challenge with most countries having incomplete data on numbers of cases and wide variation between health system access and performance. Regular estimates are published by the World Health Organization (WHO), but these are not split by species, can have a wide range of uncertainty, change over time and are not available for every year.

Methods: For the Asia Pacific Leaders Malaria Alliance, the burden of malaria for the 22 malaria-endemic countries in the Asia-Pacific from 2000 to 2015 was estimated by combining data submitted by countries to WHO with a systematic review to estimate the proportion of cases recorded. Due to a lack of suitable data, it was only possible to apply this method to 2013-2015. A simplified method was then derived to estimate the annual burden of falciparum and vivax malaria as inputs to a mathematical model to predict the cost of elimination, which is described elsewhere.

Results: The total number of estimated cases was around double the number of confirmed cases reported in the Asia Pacific with a broad range of uncertainty around these estimates due primarily to sparsity of data with which to estimate proportions of cases reported. The ranges of estimated burdens were mostly like those published for countries by WHO, with some exceptions.

Conclusions: The accuracy and precision of malaria burden estimates could be greatly improved by having more regular large surveys on access to healthcare in malaria-endemic areas and making subnational data on malaria incidence and reporting completeness publicly available.
**Introduction**

The Asia-Pacific aims to eliminate malaria by 2030, with individual countries having much earlier national targets for each of *P. falciparum* and *P. vivax*. For malaria elimination to succeed, it is essential to have an accurate picture of malaria incidence over time and space. However, in many countries the burden of malaria is grossly under-reported. Under-reporting of malaria incidence greatly impedes allocation of appropriate resources within governments and improves efficient targeting of appropriate malaria control interventions. It also constrains allocation of external funding from donors (e.g. The Global Fund), which is determined predominantly by the disease burden and economic capacity of the country\(^1\). A complete and accurate picture of malaria incidence is essential for a country to show reliable evidence they are moving towards elimination. Additionally, harmonization of reliable and complete data between countries facilitates direct comparability of datasets across international borders. Ongoing efforts to increase this harmonization will help underpin regional conversations about malaria elimination and greatly improve coordination between National Malaria Control Programmes (NMCPs).

There are several contributors to under-reporting of malaria. Most NMCPs routinely collect malaria incidence data from government health centres, but the extent to which data from hospitals and community health workers are included in the national dataset varies greatly\(^2\). Information on patients presenting to other health services, including non-governmental organizations (NGOs) and the private sector, as well as the military and mobile and migrant populations (both often higher risk for malaria), are also frequently omitted from the national totals and from the data reported to the World Health Organization (WHO) as many NMCPs do not have access to this information. For those facilities that do report data to the NMCP, the data itself may be incomplete due to missing reports. This may not always be apparent to the NMCP in countries where facility-level data is aggregated at the district or province level prior to collation in the national database. Finally, not all malaria cases may receive a diagnostic test, thus excluding them from the number of confirmed cases.

Several methods have been developed to estimate the true burden of malaria. Two of these are used by the World Health Organization for the annual World Malaria Report (WMR) published towards the end of each year which provides a point estimate together with a range from lower and upper estimates for total cases in each country\(^3\). In high-transmission countries in Africa, a geostatistical model including environmental and sociodemographic covariates is used to estimate annual cases from malaria prevalence surveys. In countries outside of Africa and low-transmission countries in Africa, the number of reported malaria cases is adjusted for completeness of reporting, the likelihood that cases were parasite-positive, and the extent of health-service use to estimate numbers of cases. This method uses data submitted annually by NMCPs and nationally representative household surveys of healthcare use, which are not done in many countries. Although widely quoted, the burden estimates by WHO are not broken down by species, can have a wide range of uncertainty, are not published for every year (e.g. 2014) and the numbers are revised periodically. Country-level estimates have been published for 2006\(^6\), 2010\(^7\), 2012\(^8\) and 2013\(^9\) with revised estimates for 2000, 2005, 2010 and 2015 in 2016\(^10\). In 2017\(^11\), annual country-level estimates were published for 2010–2016. These were different to those published previously and were substantially revised with new estimates for 2010–2017 in WMR 2018\(^12\). These gaps and changes over time make it impossible to reconstruct an annual trend in estimated incidence by country since 2000 from these reports. However, annual detailed data on numbers of cases reported by each country including a breakdown by species and diagnostic method and a wealth of other information are provided in the annexes of these reports.

In 2014, the Asia Pacific Leaders Malaria Alliance (APLMA) secured agreement from the East Asia Summit Heads of Government for the Asia Pacific region to become free of malaria by 2030. Supported by the Australian government and Asian Development Bank, APLMA worked with a range of partners, including Mahidol Oxford Tropical Medicine Research Unit (MORU) in 2016 and 2017, to build an evidence base to inform decisions on malaria elimination. As part of this, MORU developed a report on the status of malaria elimination in the Asia Pacific including a survey on current sources of malaria surveillance data collected by NMCPs and the role of the private sector in malaria treatment in the Asia Pacific region\(^13\), together with estimates of the range of possible annual disease burdens in each country in 2014 and 2015. This required development of a new and transparent methodology using publicly available data. In a follow-on project for APLMA supported by Asian Development Bank, these annual estimates were then extended to cover the period 2000 to 2015. This was done in order to parameterise a mathematical and economic model to predict the cost of regional elimination and the return on investment under a range of scenarios. Details of the model and results of the economic analysis are published in other manuscripts in this collection\(^11,12\).

The methodology and results of the disease burden estimates are presented in this paper including a systematic review on treatment-seeking behaviour and comparison with WHO estimates for selected years.

**Methods**

**Data analysis**

Data were analysed in Excel 2016 (Microsoft, WA, USA) and GraphPad Prism 8.0.1 (GraphPad Software Inc., CA, USA) in 2016 and 2017. Three methods were used to estimate the burden of malaria, the choice of method depending on the available data in each year.

**Method 1**

The true burden of clinical malaria (b\(_{\text{true}}\)) in 2013, 2014 and 2015 was estimated at country level for each of total burden, *P. falciparum* and *P. vivax* using the method described here. This combined information on malaria incidence and completeness of reporting from the WHO World Malaria Reports (WMR) 2014\(^1\), 2015\(^1\) and 2016\(^1\) with the sensitivity of diagnostic tests used and estimates of the proportions of patients recorded by the malaria surveillance systems in each country. The latter were
The methodology for the systematic review of published reports on treatment-seeking behaviour. The burden estimates for 2015 were compared with estimates derived by WHO for the WMR 2016. Details of the methods used by the WHO can be found in the 2008 WMR. Briefly, for the Asia-Pacific, these use data reported by NMCPs on numbers of cases, completeness of reporting and the likelihood that cases were parasite positive and data from nationally representative surveys on the extent of health service use. It was not possible to compare estimates for 2014 with WHO estimates as no estimates were published for that year, the 2015 WMR containing estimates from 2013.

The true burden of malaria (B_TRUE) in 2013, 2014 and 2015 was estimated to derive national median, minimum and maximum estimates for each of total malaria burden, P. falciparum and P. vivax per country using the following equation:

$$B_{TRUE} = \frac{1}{P_{rec}} \left( \frac{B_{confTOT} * P_{rec}}{S_{mic}} + \frac{B_{confTOT} * P_{RDT}}{S_{RDT}} \right) * \frac{1}{P_{comp}}$$

Where:

- $P_{rec}$ = the proportion of those with malaria who are recorded in each country. As it is not possible to measure this parameter directly, as a proxy, the proportion of individuals with malaria or undiagnosed fever presenting to health facilities or community based treatment programmes in each country was used. This assumed these cases would be recorded in the national surveillance database and that cases who presented to the private sector would not. To estimate $P_{rec}$, a range of values for each country were derived from a systematic review of published literature on treatment seeking behaviour in each country, described below with search terms in extended information, Table S1.

- $B_{confTOT}$ = the total number of confirmed malaria cases in each country in 2013, 2014 and 2015. This was the sum of the number of confirmed malaria cases in Public Health Facilities and Community Treatment Programs in each country in the WMR 2014, WMR 2015 and WMR 2016. Mixed infections (P. falciparum plus P. vivax) were included in the numbers for each species. Numbers of unconfirmed cases were not included due to the large uncertainty in the proportions of these cases likely to have malaria and the introduction of mandatory malaria testing in all the Asia-Pacific countries prior to 2012. These data are provided in the appendices of the respective WMRs.

- $P_{mic}$ = the proportion of confirmed cases diagnosed in each country by microscopy in 2013, 2014 and 2015. These data are provided in the extended data, Table S2.

- $P_{RDT}$ = (1 - $P_{mic}$) = the proportion of confirmed cases diagnosed in each country by rapid diagnostic test (RDT) in 2013, 2014 and 2015. These data are provided as extended data, Table S2.

- $S_{mic}$ = sensitivity of microscopy = 95% (range 90–100%). The lower end of this range was set at the WHO minimum level of competency for malaria microscopists.

- $S_{RDT}$ = sensitivity of RDT = 95% (75–100%) for P. falciparum and 90% (50–100%) for P. vivax and other Plasmodium species. The true sensitivity of RDTs in field conditions varies widely between manufacturers and in different field conditions, as well as being greatly affected by parasitaemia, as reported in detail following extensive testing by WHO. The values used were derived from the ranges of sensitivities found in these tests.

- $P_{comp}$ = the completeness of reporting i.e. the proportion of expected reports which were received by the NMCP. Values for this were taken directly from the data provided by countries to WHO for the WMRs on completeness of reporting by public health facilities. $P_{comp}$ was calculated by the countries from the total number of health facility reports received by a ministry of health during a year, divided by the total number of facility reports that were expected in that year. The expected number of facility reports was the number of health facilities multiplied by the frequency of reporting; that is, if 100 facilities were expected to report each month, 1200 reports would be expected during a year. Where no values were available, this was assumed to be 100% to give the most conservatively high disease burden estimate. These data are provided in the extended data, Table S2. No data on completeness of reporting were available for cases at community level so this was assumed to be the same as public health facility cases.

Systematic review. The methodology for the systematic review is described in detail on PROSPERO, under registration CRD42016032564. The following inclusion criteria were used: English language, human studies, quantitative or mixed methods, enumeration of public and/or private sector health-care seeking behaviour for malaria/fever/febrile illness and/or published from 2000 onwards. Sources included Pubmed (fixed search terms are given as extended data, Table S1), hand search of reference lists from identified articles, publically available grey literature, Demographic and Health Surveys (DHS) and UNICEF Multiple Indicator Cluster Surveys (MICS). The search was done in 2015. Studies were screened for duplications and assessed for quality using published criteria. In total, 2637 relevant sources were identified. Of these, 20 could not be obtained in full-text. Of the remainder, 70 studies met the inclusion and quality criteria and were thus used for this analysis. A value for $P_{rec}$ was derived from the results of each included study and the median, minimum and maximum values for each country used in the analysis. The surveys were all treated equally with no weighting for recency, geographic or demographic coverage of the data in order to output the widest range of possible values.

Results were correlated with estimates for 2013 and 2015 in the WMRs.

Method 2
For 2000 to 2008, data on completeness of reporting were not available. From 2000 to 2012, numbers of confirmed cases at community level, and numbers of cases by diagnostic method for community cases were not available. Therefore as an alternative approach, the burden estimates calculated for 2014...
were used to calculate the ratio of estimated cases to reported cases in public health facilities for each species and this ratio was used to derive estimates of *P. falciparum* and *P. vivax* for 2000 to 2013 for the modelling. This was done by multiplying this ratio by the annual number of reported confirmed public health facility-reported cases of each species in 2000 to 2013, provided in the appendices of the WMR 2015. These data are provided as extended data, Table S3. This carried the assumptions that the proportion of confirmed cases identified in the community and completeness of reporting did not change during this period. The ratios are provided as extended data (Table S3). To validate this method, the median, minimum and maximum burdens for each species were correlated with those derived for 2013 using Method 1 and the trends over time compared with the burden estimates for total cases in the 2016 WMR.

**Method 3**

In the data in the WMRs, there were found to be some discrepancies in the total numbers of cases by diagnostic method and by species. To address this, a third alternative method was applied to data from 2000 to 2014 to estimate the numbers of confirmed *falciparum* and *vivax* cases at public health facilities by multiplying the numbers of confirmed cases diagnosed by microscopy and RDT by the proportion reported with each *Plasmodium* species. This was then adjusted for the sensitivity of microscopy and RDT, access to healthcare and completeness of reporting, as outlined for Method 1. For years in which completeness of reporting was not available for a particular country, it was assumed to be 100%. Validation was then done by comparing the estimated median, minimum and maximum with calculated values using Method 2 for 2013. Trends over time by country for 2000 to 2015 using Methods 2 and 3 were then compared to the available data from the World Malaria Report to select the preferred method to derive estimates for the modelling.

**Results**

**Proportion of cases recorded**

The results of the systematic review on proportion of cases recorded are in Table 1. Out of the included 70 surveys, 22 covered the whole country, of which 20 were DHS or MICS, and the others were mostly limited to a single subnational unit (subdistrict, district, province). Most of the data were from before 2013. In three countries, the most recent data were from 2013 using Method 1 and the trends over time compared with the burden estimates for total cases in the 2016 WMR.

### Table 1. Results of systematic review to estimate the proportion of those with malaria who are recorded in each country.

<table>
<thead>
<tr>
<th>Country</th>
<th>Number of sources</th>
<th>References</th>
<th>Most recent data</th>
<th>Cover whole country</th>
<th>Estimated proportion recorded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Median</td>
</tr>
<tr>
<td>Afghanistan</td>
<td>2</td>
<td>18,19</td>
<td>2011</td>
<td>1</td>
<td>67.6%</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>6</td>
<td>20–25</td>
<td>2013</td>
<td>4</td>
<td>70%</td>
</tr>
<tr>
<td>Bhutan</td>
<td>1</td>
<td>26</td>
<td>2010</td>
<td>1</td>
<td>74.2%</td>
</tr>
<tr>
<td>Cambodia</td>
<td>9</td>
<td>27–35</td>
<td>2014</td>
<td>3</td>
<td>61%</td>
</tr>
<tr>
<td>DPR Korea</td>
<td>1</td>
<td>36</td>
<td>2009</td>
<td>1</td>
<td>74.6%</td>
</tr>
<tr>
<td>India</td>
<td>10</td>
<td>37–46</td>
<td>2011</td>
<td>1</td>
<td>60%</td>
</tr>
<tr>
<td>Indonesia</td>
<td>5</td>
<td>47–51</td>
<td>2012</td>
<td>1</td>
<td>42%</td>
</tr>
<tr>
<td>Lao PDR</td>
<td>4</td>
<td>52–55</td>
<td>2012</td>
<td>1</td>
<td>46%</td>
</tr>
<tr>
<td>Malaysia</td>
<td>1</td>
<td>56</td>
<td>2009</td>
<td>0</td>
<td>81.6%</td>
</tr>
<tr>
<td>Myanmar</td>
<td>7</td>
<td>57–63</td>
<td>2013</td>
<td>1</td>
<td>48%</td>
</tr>
<tr>
<td>Nepal</td>
<td>4</td>
<td>64–67</td>
<td>2014</td>
<td>2</td>
<td>44%</td>
</tr>
<tr>
<td>Pakistan</td>
<td>5</td>
<td>68–72</td>
<td>2014</td>
<td>1</td>
<td>65%</td>
</tr>
<tr>
<td>Papua New Guinea</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Philippines</td>
<td>3</td>
<td>73–75</td>
<td>2013</td>
<td>1</td>
<td>50%</td>
</tr>
<tr>
<td>PR China</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Republic of Korea</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Solomon Islands</td>
<td>1</td>
<td>76</td>
<td>1999</td>
<td>0</td>
<td>97%</td>
</tr>
<tr>
<td>Sri Lanka</td>
<td>2</td>
<td>77,78</td>
<td>2001</td>
<td>0</td>
<td>75.9%</td>
</tr>
<tr>
<td>Thailand</td>
<td>4</td>
<td>29,79–81*</td>
<td>2013</td>
<td>1</td>
<td>58.1%</td>
</tr>
<tr>
<td>Timor-Leste</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Vanuatu</td>
<td>1</td>
<td>82</td>
<td>2007</td>
<td>1</td>
<td>73.2%</td>
</tr>
<tr>
<td>Viet Nam</td>
<td>6</td>
<td>53,83–87*</td>
<td>2014</td>
<td>2</td>
<td>56%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>70</strong>*</td>
<td></td>
<td></td>
<td><strong>22</strong></td>
<td><strong>N/A</strong></td>
</tr>
</tbody>
</table>

*Actual total was 72 but two sources had data for two countries.*
2014 (whole country: Cambodia and Viet Nam, one province: Pakistan) and in four from 2013 (whole country: Bangladesh and Philippines; one township: Myanmar; five provinces: Thailand). The DHS and MICS surveys were the largest with mostly whole country coverage but were specific only to children whereas much of the burden of malaria in the Asia-Pacific is in adults. Nationally representative surveys were found for 15 countries, only subnational for three (Malaysia, Solomon Islands and Sri Lanka) and no surveys were found for four countries. Regarding national surveys, 12 countries had data from MICS, seven from DHS and four from both DHS and MICS.

Burden Estimates for 2013 to 2015

The malaria burden estimates for each country in 2013, 2014 and 2015 derived using Method 1 are presented in Figure 1 and extended data, Table S5A-C. The total estimated burden for the 22 countries in 2015 was median (range) 2,784,441 (1,764,116–17,864,485) \( P. falciparum \), 2,056,221 (1,372,338–13,281,356) \( P. vivax \), 5,222 (4,684–7,782) other species and 4,809,884 (3,141,137–31,153,623) total cases. This total was around two times greater than the total number of confirmed cases reported to WHO in each of these years.

The precision of these estimates was greatly influenced by the lack of suitable recent studies on access to healthcare to estimate the proportion of cases reported for the 22 countries and by a lack of data on completeness of reporting for confirmed community cases. For comparison, the estimates for total malaria burden in 2015 published in the WMR 2016 are also shown as extended data, Table 5C and graphically in Figure 2. The median, minimum and maximum estimates by country correlated strongly with the WHO estimates (r=0.9661, 0.9570 and 0.8778, respectively). Although estimates for many countries were quite similar between the two methods, the overall WHO point estimate was 3.6 times higher. This discrepancy was mainly due to an almost eight times higher point estimate by WHO for India due to inclusion of the number of unconfirmed malaria cases in the WHO calculation. Of note, both methods found a similar upper bound for total cases in India of around 18,000,000. Other countries with substantial differences between the two were Bangladesh, where the WHO estimate was lower, and Nepal, where it was higher. In Bangladesh this was due to most confirmed cases being reported at community level (6,608 public health facility vs 32,992 community in 2015) as most malaria testing and treatment in the country is done by the Bangladesh Rural Advancement Committee (BRAC) consortium and not at public health facilities run by the government. The reason for the WHO estimate for Nepal being much higher is not clear, although at 1,112 reported cases and 24,000 (17,000–35,000) estimated cases, this represents a 21.6-fold increase for the Point estimate, which is by far the highest of any country in the Asia-Pacific. For comparison, Method 1 found a median of a 3.4-fold increase.

The burden estimates for 2014 could not be compared with WHO estimates for that year as no estimates were published for 2014. In the 2015 WMR, country-level estimates were provided for 2013 and regional level estimates were provided for 2015. These 2015 estimates were then revised downwards in the 2016 WMR.

Comparing median, minimum and maximum estimates for 2013 using Method 1 with those for 2013 from WHO (Figure 3), again found them to be highly correlated (r=0.8970, 0.9109 and 08409, respectively), although less strongly than for 2015. There were some notable differences between Method 1 and WHO. Median estimates for Timor Leste, Bangladesh, India and Indonesia were markedly lower than those from WHO. These countries all had very high ratios of estimated cases to reported cases in 2013 in the WMR (59, 26, 15 and 10, respectively). Both Timor Leste and Bangladesh had very large decreases in cases estimated by WHO from 2013 to 2015 (750-fold and 83-fold). With reported confirmed cases decreasing only 12-fold in Timor and increasing 1.8-fold in Bangladesh in the same period, and no other clear explanation for such a large change, the estimates in 2013 seem to be too high. India had a 1.3-fold decrease.

Figure 1. Numbers of estimated \( P. falciparum \), \( P. vivax \) and total malaria cases in 2013, 2014 and 2015 by country using Method 1. Median and range are shown.
in cases estimated by WHO from 2013 to 2015 and Indonesia 3.2-fold. Similar to 2015, the higher number of cases in the WHO estimates appear to be due to inclusion of the large numbers of unconfirmed cases in the calculations. Maximum estimates for Cambodia, Lao PDR, Viet Nam and Myanmar were much higher than those from WHO due primarily to the wider range of sources used to quantify the proportion of cases which are reported.

A comparison of results for 2013 using Methods 1 (calculation method) and 2 (ratio method) is shown in Figure 4. The results were very similar for all countries for both *P. falciparum* and *P. vivax* (r=0.9873, 0.9782 and 0.9873 for median, minimum and maximum *P. falciparum* and 0.9870, 0.9896 and 0.9922 for *P. vivax*) with no marked differences for any country.

**Burden estimates for 2000 to 2014**

Numbers of reported confirmed cases, and disease burden estimates for each species by country from 2000 to 2015 using Methods 2 and 3 are shown in Figure 5 with reported numbers of confirmed cases in Figure 6A-C. Methods 2 and 3 differed in that Method 3 generally gave lower overall estimated totals for the Asia-Pacific before 2009 with a relatively flat trend over time. The two methods gave very similar overall results from 2012 onwards. In contrast, Method 2 produced a clear downward trend in both falciparum from 2000 to 2015 and vivax from 2005 to 2015. WHO estimates for 2000, 2005, 2010 and 2015 also showed a marked downward trend, especially from 2005 to 2015 (Figure 6D-F). Using Method 2, the estimated cases were lower in Myanmar in 2007 to 2011 and in Papua New Guinea in 2012 and 2013 due to the numbers of confirmed cases by microscopy and RDT being far higher than the total numbers reported for each species. Compared to Method 2, Method 3 produced lower numbers of *P. falciparum* in Bangladesh prior to 2012. This was due to the majority of cases being diagnosed in the community in Bangladesh and numbers of cases by species in the community only being included in the totals before 2012. In the Philippines in 2000 to 2006, Method 3 was found to give fewer estimated cases as there were no data on numbers of confirmed cases by microscopy and RDT but there were data on numbers of each species.

**Burden estimates for modelling**

Method 2 was chosen to derive estimates for the modeling as it better captured the trend in estimated cases over time seen in the estimates from WHO. Results of the disease burden estimates

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**Figure 2.** Number of estimated total malaria cases in 2015 by country using Method 1 and from WHO WMR 2016. Median and range are shown. Dashed lines in B are the identity lines.
Figure 3. Number of estimated total malaria cases in 2013 by country using Method 1 and from WHO WMR 2015. Median and range are shown. Dashed lines in B are the identify lines.

Discussion
The study attempted to develop a simple method to calculate annual estimates by parasite species of malaria disease burden for the 22 endemic countries in the Asia-Pacific from 2000 to 2015 using publicly available data. It was found that the overall resulting estimated numbers of cases were roughly double the numbers that were reported. However, there was an approximate 10-fold range of uncertainty around these estimates. This uncertainty was similar in scale to the estimated total numbers of cases in the same countries published by WHO in the annual WMRs. Although the methods were broadly similar, estimates for particular countries varied between the two due to differences in the data used. One major difference is that the WHO estimates include numbers of unconfirmed cases, whereas this study did not. In India, this may have caused the point estimates from WHO to be more than 10 times higher due to the more than 100 million suspected cases reported each year, although this was compensated for by the broader range of values for the proportion recorded in the present study which resulted in similar maximum estimates. It was decided not to include unconfirmed cases in the present analysis as mandatory diagnostic testing for malaria has been widely adopted in health facilities in the Asia-Pacific, as recommended by WHO since 2010, and those who do not attend a health facility would be included in the proportion of unrecorded cases.

The primary contributor to the uncertainty of the derived estimates in the present study was the wide range of values for the proportion of cases which are recorded. In an attempt to include data from a broad range of sources, these were collected from a systematic review of the published literature. Despite widely searching both the academic and grey literature, there were relatively few suitable studies and none at all in some countries. Thus many of the studies that were included were not recent and there was insufficient data to assess how much this value might change over time in each country. An analysis of estimates from DHS and MICS by WHO in 2008 found that the proportion of people with fever using health facilities covered by the reporting system did not change substantially over time. For 2000 to 2014 derived using Method 2 that were used in the modelling are provided in the extended data (Tables S6A-F).
Figure 4. Comparison of malaria burden estimates for each species in 2013 using calculation method (Method 1) vs ratio method (Method 2). Dashed lines are the identity lines.

However, data for any particular country was sparse with only 58 year-to-year comparisons across all malaria endemic countries. With substantial investments in malaria in recent years across the Asia-Pacific, and expansion of village malaria worker networks particularly in the Greater Mekong Subregion, it seems likely that access to healthcare should have improved since 2000, but this is difficult to measure with current available evidence.

DHS and MICS are large nationally representative surveys that were included among the sources for quantifying the proportion of cases recorded in the present study. They are also the primary source of this data for this parameter used in the WHO WMR estimates for the Asia-Pacific. The DHS and MICS are surveys of children under 5 years of age. A limitation of this for the Asia-Pacific is that a high proportion of those with malaria are older children and adults and it is not clear if their...
health-seeking behaviour is different to young children as suggested in some studies\textsuperscript{37}. Another limitation is that these surveys are not always representative of malaria endemic areas whose populations may have lower income and poorer access to healthcare\textsuperscript{90, 91}.

It is worth focusing a little more on India, as the country with by far the highest reported and estimated burden. The difficulty estimating, and high degree of uncertainty of, the true burden of malaria in India have been highlighted by previous studies\textsuperscript{89, 92}. One used a geostatistical method to estimate the number of cases and deaths in 2006 to be far higher than that estimated by WHO\textsuperscript{92}. Inadequacies in reporting and the health management information system were highlighted as contributing to the uncertainty. In the present study, 10 citations from India were included for estimating the proportion of cases reported, the most from any country; however, only one of these was nationally representative and the most recent was from 2011 and estimates ranged from 7\% to 93\%. Since then, a further DHS was done in India in 2015-16, which had no specific questions about malaria but found that 73\% of children with fever are taken to a health facility or provider\textsuperscript{93}. There is clearly a need for more robust measures of access to healthcare to improve estimates for India.

In this study, detailed calculations could be made only for 2013–2015 due to a lack of data on the required parameters. Although the initial intention was to apply a single method to annual data from 2000 to 2014 to use in modelling the cost of elimination, it was found that some of the parameters used in the estimates were not available for earlier years. Therefore two simplified versions of the equation using fewer parameters were also developed and the method that most closely reproduced the trends in reported cases and the WHO estimates was adopted for the modelling. The final approach adopted for these estimates was calculation of a ratio of estimated cases to reported confirmed health facility cases. This is similar to a method that has been proposed for estimating the burden of dengue where the number of reported cases is multiplied by an expansion factor (EF)\textsuperscript{94}. Available data for dengue is much less comprehensive than for malaria and therefore EF has been calculated from published studies and from extrapolation based on available metrics of the quality of healthcare. The limitations of the former are that there are few

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**Figure 5.** Median annual estimated numbers of cases using Methods 2 and 3 of *P. falciparum* and *P. vivax* in the Asia-Pacific 2000–2015.
relevant studies and that the studies mostly only covered small parts of each country and a limitation of the latter is that it uses broad metrics of healthcare quality, e.g. physician density and child mortality that are not proven to be related to dengue reporting rates. Unlike malaria, most cases of dengue do not have a confirmatory diagnostic test so the number of reported cases includes people who do not have dengue. These all contribute to wide uncertainty in estimates of dengue but may be worth considering for malaria, for which the data, despite the problems, is generally better.

For the present study, in addition to the limitations due to lack of available data for particular years, there are a number of other limitations to the analysis which should be highlighted. Over the period 2000 to 2015, there have been changes to the health systems in each country, which are difficult to account for in the analysis. Examples include the initiation of a mandatory requirement to confirm all reported cases with a diagnostic test and the introduction and subsequent roll-out of falciparum RDTs followed by RDTs for multiple species, particularly in the community in different years in different countries. There have also been changes in coverage of health services (mostly improvements) during this time. All of these have occurred gradually and have the potential to increase numbers of confirmed malaria cases in the data, but their impact on the totals is difficult to quantify and adjust for. The simple approach adopted here, to use ratios based on 2014 estimates, would at least partially account for these as all countries had adopted mandatory testing and most had adopted RDTs by this time.

It was also not possible to fully account for some differences between health systems which impact on the way data are reported. For example, the numbers of cases reported to WHO are divided into those reported by public health facilities and cases at community level. The estimates by WHO use numbers of public health facility cases as these are usually the majority and are thought to be more reliable. Much less information is therefore provided in the WMR for the cases at community level, with data not broken down by species and completeness of reporting not being included. For example, in Bangladesh the majority of malaria testing is done by Bangladesh Rural Advancement Committee (BRAC), and reported as community cases with only a minority being public health facility cases. This resulted in much lower estimates of cases in Bangladesh by WHO compared to this study in 2013 and 2015.

The direct consequence of uncertainty in the burden estimates for this particular study was uncertainty in the modelling results that are driven by this data. In this case, the predicted cost and return on investment for elimination are the main results of the modelling and had a range of possible values for any possible scenario. Whilst it may be helpful as a general indication of the scale of investment required, to inform detailed budget planning, particularly for individual countries, and to guide allocation of finite resources between countries would require much more precise estimates.

Other methods which have been used to estimate malaria burden estimates include the Global Burden of Disease Study, which used three different techniques depending on the availability and quality of malaria incidence data: 1) using regression on mortality data, age group and modelled parasite positivity ratio (PnP); 2) by regression on national level PnP estimates; and 3) using case data from the WMR. For Asia-Pacific countries, all three

Figure 6. Annual numbers of confirmed cases reported in the 2015 and 2016 WMRs (A. all confirmed by microscopy or RDT, B. P. falciparum and C. P. vivax) and estimated numbers of cases reported in the 2016 WMR (D. Point, E. Lower and F. Upper) in the Asia-Pacific from 2000 to 2015.
methods were used. There were substantial differences from the WHO estimates and the authors discuss the various contributors to these differences in detail including challenges of inadequate available data. An alternative approach for areas with very poor data has been to use incidence and prevalence data from published studies in Africa to develop a transmission dynamic mathematical model including immunity, which predicts the age distribution and annual incidence of clinical disease\textsuperscript{46}. Such an approach is limited by available research data from heterogeneous study designs, is affected by measures of health-seeking and requires a number of assumptions to be made including about malaria biology and transmission in the country being modelled. The geostatistical model used to derive estimates for WHO for high burden countries in Africa has also been applied to estimate global malaria burden\textsuperscript{47}. This uses a Bayesian framework with multiple spatially highly resolved covariates to generate detailed predicted prevalence surfaces from which an estimated range of incidence is derived. This method continues to be refined and updated maps and predicted estimates are published on the project website (https://map.ox.ac.uk/). One recent development has been the use of serology data to quantify recent malaria infections\textsuperscript{48}. Studies are ongoing to assess how well seropositivity rates might predict malaria incidence.

The precision and accuracy of malaria burden estimates could be improved by changes in the collection and availability of data. Examples highlighted by the present analysis include having more regular household surveys on access to healthcare for people with fever in malaria-endemic areas to estimate the proportion of cases reported in all countries, e.g. DHS and MICS. This would be most informative if done in malaria-endemic areas in the populations at risk of malaria. Completeness of reporting of cases at community level is not currently collected but could be included in the annual WMR. A lack of publicly available subnational data is a major constraint to deriving more accurate estimates with current estimates only possible at national level. As well as malaria incidence rates, it is likely that completeness of reporting, access to healthcare, and the proportion of community to public health facility cases all vary across space and these should be included in the estimates. This will also have the advantage of allowing subnational burden estimates, which will be much more informative for NMCPs when deciding on allocation of resources.

Conclusions
Estimating the true burden of malaria is essential to help guide allocation of resources for malaria elimination. Limitations in the available data make estimating true burden and predicting cost of elimination very imprecise. Having more publicly available data from NMCPs, more regular surveys on access to healthcare and access to subnational data could greatly improve these estimates.

Data availability
Underlying data
The data used in this manuscript are taken from the WHO World Malaria Reports, which are available online at: https://www.who.int/malaria/publications/world_malaria_report/en/.

Extended data

The following extended data are available:

- Supplementary Material Tables S1 to S3.doc.
  - Table S1. Search terms for literature review on healthcare seeking behaviour.
  - Table S2. Completeness of reporting by health facilities (P\textsubscript{com}), proportion of cases diagnosed by microscopy (P\textsubscript{mic}) and proportion of cases diagnosed by RDT (P\textsubscript{RDT}).
  - Table S3. Composite ratio of burden estimates to public health facility cases in 2014 for \textit{P. falciparum} and \textit{P. vivax} for Method 2.

- Supplementary Material Table S4 Pf\textsubscript{Pv_reportedcases}.xlsx (Table S4. Numbers of confirmed \textit{P. falciparum} (A) and \textit{P. vivax} (B) cases reported by public health facilities in the WHO World Malaria Reports).

- Supplementary Material Table S5 Pf\textsubscript{Pv_Total_WHO_burden} 13-15.xlsx (Table S5. Estimated malaria disease burden for 22 countries in the Asia-Pacific in 2013 compared to 2015 (A), 2014 (B) and 2015 compared with 2016 (C) using Method 1).

- Supplementary Material Table S6 Pf\textsubscript{Pv_burdenestimates_00-14.xlsx} (Tables S6A-F. Estimated burden of \textit{P. falciparum} and \textit{P. vivax} malaria by country from 2000 to 2014 used in the modelling).

Extended data are available under the terms of the Creative Commons Zero “No rights reserved” data waiver (CC0 1.0 Public domain dedication).

Reporting guidelines

Grant information
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References

Open Peer Review

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This article concerns a fundamental topic relevant to malaria control in the Asia-Pacific: what is the actual burden and how has it changed in the face of interventions? It is clearly a substantial piece of work and analysis and I agree wholeheartedly with their conclusions around the difficulties of this process and the benefits of more regular reporting and surveys of treatment seeking behaviour. However, I have some quite major concerns about the methodology as it currently stands and, as a result, the extent to which the estimates are a reasonable reflection of burden, particularly in places with imperfect diagnosis and where a substantial proportion of individuals access care within the private sector.

Inevitably newly derived estimates of malaria burden will be compared with those that exist already, particularly those released by WHO in their annual malaria report. Alternative estimates should be welcomed – there's more than one good way to cook an egg - particularly if the methods used reflect an alternative, but justifiable, way to handle the uncertainty which, for estimation on this scale, is likely to be substantial. However, I'm confused as to why in this analysis, when comparing their estimates to WHO, the authors use those from the 2016 World Malaria Report, rather than the more recently released estimates in the 2018 version[ref-1. I'm going to advocate that the authors amend their analysis to reflect these more up-to-date estimates for two reasons:

1) I disagree with the authors when they make the following statement: "In 2017, annual country-level estimates were published for 2010–2016. These were different to those published previously and were substantially revised with new estimates for 2010–2017 in WMR 2018. These gaps and changes over time make it impossible to reconstruct an annual trend in estimated incidence by country since 2000 from these reports". I think that revising historical estimates as new data and methods become available is a hugely important process and should be welcomed (not least because it's precisely what the authors themselves are attempting to do), as long as discrepancies are understood and carefully investigated this process should make reconstructing annual trends more reliable rather than impossible and subsequent revisions, or attempts to improve upon estimates, should use the most up-to-date methodology and data as the gold standard. The
current estimates by WHO also have estimates for each year.

2) The latest version of the WMR has a comprehensive section which detailed the methods used to obtain estimates, making understanding differences between the WHO estimates and those in this paper far more straightforward (especially as they are often using the same data inputs). It reveals two key differences from the methods used by the authors – firstly WHO attempts to account for individuals with suspected malaria who do not receive a diagnostic test by extrapolating the test positivity for malaria in those tested, secondly they provide a clear accounting of how private sector is incorporated. In contrast the authors in this analysis do not include individuals suspected for malaria who are not tested on the basis that:

“It was decided not to include unconfirmed cases in the present analysis as mandatory diagnostic testing for malaria has been widely adopted in health facilities in the Asia-Pacific, as recommended by WHO since 2010, and those who do not attend a health facility would be included in the proportion of unrecorded cases.”

This seems a very hard argument to sustain without data – inevitably there is going to be a gap between policy (mandatory testing) and its implementation. It doesn't take long to find examples where this isn't the case (for example in PNG in 2014 about 40% of children with fever accessed care, of these about 25% - 10% of all fevers - received a test for malaria\(^2\)). Clearly WHO's method where they extrapolate test positivity in the 25% receiving a test to the remaining 75% accessing care contains assumptions but personally I would pick that approach over the implicit assumption the authors make that there is no burden to be accounted for within that 75%...

In contrast to the WHO who now give a clear accounting for how private sector care seeking (and uncertainty) is incorporated, in particular for India where this is done at a sub-national level, here the authors incorporate all of this uncertainty (private/public/seek care/don't seek care etc.) within a single term \(P_{rec}\) and provide no formula for how either the median or range of these values are calculated (at least that I can find – many apologies if I missed it buried in the S.I! – if so I would suggest moving to main text).

A more careful accounting for this calculation by the authors would allow the reader to assess the reasons and merits of the major discrepancies between some estimates: for example, in my opinion, the 10 fold, >10 million case discrepancy between the estimates of WHO and the authors can, and should, be explained and investigated in more detail than simply because “[WHO] include numbers of unconfirmed cases”. I agree that some other discrepancies seem harder to explain (e.g. Nepal) from WMR 2016 but it is noticeable in the Nepal example that the estimates for WMR 2018 are broadly in-line with the authors’ which I think is another argument for amending the analysis to contrast with the most up-to-date version.

Other suggestions/questions:
When the authors can find no estimate for reporting completeness they “assume 100% to give the most conservatively high burden of disease” – apart from questions as to why it is necessarily advantageous to be conservatively high, and that other assumptions do not err towards high burden – is this not contrarily the least conservative assumption in that respect? From the formula and intuition I would guess assuming less complete reporting would revise estimates upwards?

Apologies again if I've misconstrued.
The authors do what appears to be a highly comprehensive review of the literature but my guess is that, as it was done in 2015 and given publication timelines, there will be a lot of additional data out there now, particular for 2015 estimates. Even more recent estimates might have added value, particularly for settings like PNG where no previous data was found (e.g. the 2016-17 survey referenced\(^2\)). I’d recommend repeating the search and updating.

It’s really not clear how uncertainty is accounted for, as well as having more information as to how the % of cases reported is obtained from the literature. I’d like to know how the range was defined and how uncertainty is propagated throughout the analysis. In particular for their region-wide total upper and lower bounds of burden they simply sum the upper and lower bounds of each individual country. I don’t think this is the optimal way to represent uncertainty (akin to representing the uncertainty range of 1000 coin tosses as \([0-1000]\), in some ways it’s true but it isn’t very useful...). Even doing something simple like drawing values from triangle distributions between ranges of uncertainty and representing 95% interval would probably give more informative overall indication of the likely range.

**References**

**Is the work clearly and accurately presented and does it cite the current literature?**
Partly

**Is the study design appropriate and is the work technically sound?**
Partly

**Are sufficient details of methods and analysis provided to allow replication by others?**
No

**If applicable, is the statistical analysis and its interpretation appropriate?**
No

**Are all the source data underlying the results available to ensure full reproducibility?**
Yes

**Are the conclusions drawn adequately supported by the results?**
Partly

**Competing Interests:** No competing interests were disclosed.

**Reviewer Expertise:** Mathematical modelling and data analysis applied to malaria epidemiology.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.
The manuscript is a comprehensive evaluation of the disease estimates of the only global official source of country malaria data, the WHO World Malaria Report. The authors have also raised in their discussion a number of factors that affect quality data not only for malaria but for other health indicators. They estimated malaria disease burden using the information obtained from the WHO World Malaria Report during the period after the introduction of two interventions that have positively affected disease burden in the Asia Pacific region – deployment of malaria RDTs and ACTs.

1. The heterogeneity of malaria among, and within countries of the Asia Pacific is becoming more pronounced, and it is likely that countries might give less attention to the quality of sub-national malaria data as disease reporting approaches zero cases. What other routinely collected data at sub-national facilities, including community health facilities, could possibly serve as an indicator of coverage? Could the authors provide what are there to be learned from other disease programs?

2. WHO WMR 2008 (page 153/215) adjusts the for the number of positive-parasite cases. The authors define \( B_{\text{confTOT}} \) as the number of confirmed malaria case in the WMR. Thus, when estimating for true burden of malaria, could the authors clarify whether \( B_{\text{TRUE}} \) is a value that has been adjusted two times?

3. WHO WMR 2008 (page 153/215) adjusts the for the number of positive-parasite cases. The authors define \( B_{\text{confTOT}} \) as the number of confirmed malaria case in the WMR. Thus, when estimating for true burden of malaria, could the authors clarify whether \( B_{\text{TRUE}} \) is a value that has been adjusted two times?

4. What was the purpose of using the incidence estimates from the WMR? Was it to demonstrate the mechanics of the proposed formulae? Or to estimate malaria burden? If it was to estimate malaria burden, there might have been an accidental overestimate as the WMR estimates were already adjusted for reporting completeness and health seeking patterns. This could also be one of the reasons why the estimates for the manuscript are
almost always higher than the WMR figures even if some of the assumptions used (particularly 100% reporting rate) was supposed to underestimate the burden.

References

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and is the work technically sound?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
No

If applicable, is the statistical analysis and its interpretation appropriate?
I cannot comment. A qualified statistician is required.

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: I am a pediatric infectious diseases specialist with a PhD in tropical health. I have been involved in projects regarding malaria surveillance and reporting of the Philippines’ Department of Health. My co-referee has an MSc in epidemiology.

We confirm that we have read this submission and believe that we have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however we have significant reservations, as outlined above.