Rev Environ Health 2012;27(4):163–174 © 2012 by Walter de Gruyter • Berlin • Boston. DOI 10.1515/reveh-2012-0023

A framework for assessing and predicting the environmental health impact of infectious diseases: a case study of leptospirosis

Colleen Lau* and Paul Jagals

School of Population Health, University of Queensland, Herston, QLD, Australia

Abstract

This article demonstrates the practical application of an integrated environmental health impact assessment (IEHIA) methodology to investigate an infectious disease (leptospirosis) and the value of using such an approach to estimate future health impact. The assessment described the current health impact (using leptospirosis seroprevalence as a proxy measure) and estimated the future health impact based on scenarios that included indicators of different risk factors. The application of an IEHIA methodology to assess the health impact of an infectious disease was shown to enhance the ability to quantify associations between a disease agent and its health impact by taking into account the environmental drivers of transmission, human behaviour, socioeconomic factors, and the multiple pathways through which exposure and infection could occur.

Keywords: environmental health; infectious disease; integrated environmental health impact assessment (IEHIA); intervention; leptospirosis; public health.

Introduction

Population and environmental profiles are rapidly changing globally. Population growth and the associated consumerist demand, waste production, and mobility contribute to environmental degradation, which in turn could increase the risk of infectious diseases, chronic diseases, and injury. The World Health Organization (WHO) estimates that 25% of global disease burden can be attributed to poor environmental conditions (1). For governments and service providers in many parts of the world, it has become almost impossible to quantify the extent to which environmental hazards would impact on the health of their populations. When a health outcome could be influenced by multiple environmental hazards through a variety of concurrent exposure pathways, the assessment of environmental health impacts becomes even more complex. Consequently, there are many challenges associated with developing interventions to reduce detrimental and enhance beneficial health impacts that might result from population and environmental change.

Several tools are currently available to measure environmental health impacts (2–5) and can be found across a range of approaches and methodologies. Popular methods are mostly based on the assessment of risk posed to health by environmental contaminants including biologic agents. Arguably, the most prominent amongst these risk-based approaches would be the traditional risk assessment process (from hazard to risk characterisation), then epidemiologic studies that identify the risk factors associated with health outcomes, and finally defining the risks based on biologic measures of exposure to environmental contaminants.

The traditional environmental health risk assessments are generally implicit and quite linear in their design, striving to make sense of how health-related environmental hazards (usually single contaminants) move along exposure pathways and exposure routes (allowing for the hazard to cross the physical body barriers). If data on dose-responses for the environmental hazards are available, the overall risk of the health outcome (e.g., risk of infection or poisoning) could be estimated or predicted. However, it has become increasingly difficult to plausibly characterise (quantify or qualify) environmental health risk using this approach because of the paucity of dose-response data for the majority of environmental hazards or toxins and, often, quite extensive uncertainties surrounding the prediction. Where data are available on dose-response, their applicability to especially vulnerable subpopulations like children is often unclear. Furthermore, environmental health risk assessments are yet to fully and practically accommodate the concepts of combinations of hazardous conditions and contaminants, multiple exposure pathways, and variations in population parameters, e.g., demographics, socioeconomic status, vulnerability, education levels, and individual knowledge, practices, and behaviours (KPB) that could influence risk.

In contrast to the conventional risk assessment approach, epidemiologic assessments often tend to be more explicit because they explore and identify links between environmental hazards and health outcomes and quantify the strength of associations even if the exposure pathways, dose-responses, and behavioural risk factors were unclear. The ability to quantify relationships between environmental hazards and a health outcome is important for determining the importance of hazards (individually or in mixtures), the relative importance of each hazard, and the improvements in health that could be gained by controlling a hazard. To

*Corresponding author: Dr. Colleen Lau, P.O. Box 12426, George Street, Brisbane, QLD 4003, Australia
Phone: +61 402 134 878,
E-mail: colleen.lau@uq.edu.au
Received July 7, 2012; accepted August 16, 2012; previously published online September 12, 2012

accurately measure the cost-effectiveness and social cost-benefit of interventions, quantitative data on health outcomes would also be required (3, 6). Whilst epidemiologic studies might not provide direct proof of causality or identify the exact exposure pathway, they can be used to demonstrate or predict how changes in environmental hazard scenarios could influence the occurrence of a health outcome or provide information on effective ways of reducing the risk of an adverse health outcome. A classical example would be John Snow's success in stopping a cholera epidemic by turning off the Broad Street water pump (i.e., altering an environmental hazard and thus reducing exposure) even though the exact causative agent was unknown and the exposure pathways were poorly understood at the time (7).

The measurement of biologic markers in humans and animals allows us to detect exposure to chemicals, toxins, or biologic agents, identify the population exposed, and characterise the exposure. However, the biologic markers in themselves do not provide sufficient data on the exposure dose, exposure pathways, population parameters associated with the exposure, biologic significance of the exposure, or any associated health outcome without significant further investigation, often returning the assessor to the epidemiologic or traditional risk assessment process.

Each of the three approaches discussed above has inherent limitations, including considerable uncertainties, for assessing environmental health impact when applied separately. However, the integration of these approaches could provide a more complete assessment. Recent proposals for integrated environmental health impact assessment (IEHIA) frameworks by Briggs (8) and adapted by Knol et al. (9) show promise for a more effective integration of risk and impact assessment techniques and approaches to accommodate the assessment of the multiplicity of environmental hazards and the associated exposure pathways, population parameters, and socioeconomic influences in determining overall health impact. Such a multicriteria approach to environmental health impact assessment would also stimulate collaboration between public and private sectors that manage environment, communities, and health, thereby improving cost-benefit ratios of interventions (10). Although the concept of an IEHIA is gaining support in work done in Europe and reported in recent literature (8–10), there are limited examples of the practical application of an integrated approach to assess environmental hazards, pathways, and individual human behaviours that influence a health outcome and provide quantitative estimations or predictions of the outcome (3, 6). In particular, few studies have used an integrated approach to quantify the relative importance of environmental factors and population parameters in determining the impact of an infectious disease. For zoonotic diseases like leptospirosis, a comprehensive assessment also requires a 'One Health' approach (11), i.e., disease transmission as determined by the interaction among humans, animals, and the environments in which they coexist. Although an IEHIA methodology is well suited for investigating the complex exposure pathways and transmission dynamics associated with zoonotic diseases, this approach has not often been applied in practice.

In this article, we discuss the application of an IEHIA to quantify current and estimate future health impact of a zoonotic disease (leptospirosis) in a tropical Pacific Island setting. Whilst the IEHIA process has been proposed for the analyses of complex environmental health problems involving the full causal chain (8, 9), this case study demonstrated that this process could also be applied effectively for simpler assessments involving one hazard or disease agent (*Leptospira*) with a single disease outcome (infection) in a single population [the people of American Samoa (AS), an island nation in the South Pacific].

Case study

Leptospirosis is a globally emerging zoonotic disease with many potential drivers for infection including climate, flooding, urbanisation, environmental degradation, and human behaviour (12–16). The ecology of leptospirosis emergence is therefore highly complex and varies significantly in different epidemiologic settings. Human infections can result in a variety of clinical outcomes, ranging from mild influenza-like illnesses to severe life-threatening disease with liver failure, renal failure, and lung haemorrhage The WHO estimates that there are more than 500,000 severe cases per year globally, with case-fatality rates of up to 30% (17).

Leptospirosis is caused by an infection with *Leptospira* bacteria, which can survive for weeks in the environment. Mammals serve as reservoir hosts for leptospires, where the bacteria colonise the renal tubules of chronically infected animals and are excreted into the environment when animals urinate. There are more than 200 serovars of pathogenic *Leptospira*, each having preferences for particular species of animal hosts. Humans can be infected through direct contact with infected animals or through an environment that has been contaminated by animal urine, like water or soil (18). The transmission cycles and common exposure pathways are shown in Figure 1.

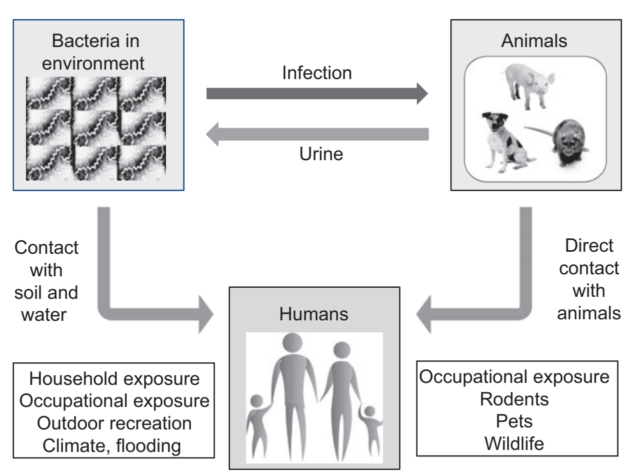

Figure 1 Transmission dynamics and common exposure pathways for human leptospirosis.

The ability to plan, implement, and sustain effective control measures for leptospirosis has been restricted by the paucity of epidemiologic and health impact data, lack of effective tools to accurately identify and especially predict high-risk areas for infection and outbreaks, and limited evidence-based strategies for public health interventions (18). The case study described here demonstrated the prognostic capability of an IEHIA to provide such information to communities and their service providers and the advantages of using an IEHIA approach when faced with the task of designing interventions to address complex environmental health issues.

The assessment ultimately provided information on the current epidemiology of leptospirosis in AS and explored possible reasons for the disease's emergence by comparing its current status to findings from a previous study (19). Using the current status as the 'reference scenario', the IEHIA also estimated the risk of infection with hypothetical 'alternative scenarios' associated with changes in the environment and/or human and animal populations.

Assessment process

Stakeholders

For an IEHIA to be successful, it is important to identify, consult, and collaborate with stakeholders as early as possible and engage them throughout the assessment process. Stakeholders are individuals who represent communities and organisations that have an interest or concern with the problem or who might be affected by the assessment's processes or outcomes (8). Stakeholders are essential for confirming the relevance of the project in the context of cultural or political issues, providing inside knowledge about the problem, and identifying questions that need to be answered. They could help appraise the appropriateness of the study design, provide valuable sources of data, and assist with logistics of conducting the assessment, including obtaining acceptance from and gaining access to target communities. For the findings of an assessment to be useful, the results need to be communicated to all stakeholders in formats that could be easily understood and applied to manage the problem. Stakeholders could also provide additional insights into the interpretation of the findings of an assessment. The presentation of findings to multiple stakeholders could be a challenging process because of inevitable differences in their background, agendas, knowledge, and ability to interpret scientific information. It is nevertheless an essential component of an assessment, not only to communicate the findings, but also to reduce chances of barriers to future access to communities that might arise from dissatisfaction caused by lack of feedback about research outcomes (8).

In the case study presented here, ongoing engagement of stakeholders was crucial for generating and maintaining local enthusiasm and support for the project, which were essential for the success of the assessment. Stakeholders included representatives of communities (village chiefs and mayors), government departments (health, commerce, environmental protection agency, Samoan Affairs), research organisations, and health-care providers (medical practitioners and the local hospital). Activities included multiple individual and group meetings, village visits, and distribution of information through local radio and television. During these activities and meetings, the study design and logistics were evaluated, valuable ideas were developed, and preexisting data were sourced from a number of stakeholders. The results were communicated through presentations to individuals and groups, printed materials, posters, local media, and publications.

Assessment frameworks

At the design and formulation stage of an IEHIA, a conceptual framework would help the assessment team to systematically explore the risk factors and complex exposure pathways, and link separate components of the assessment. The conceptual assessment framework proposed by Briggs (8) promotes the exploration of the multivariable nature of hazards and pathways and shows that risk assessment is an important component of the overall IEHIA process but is influenced by population parameters, environmental factors, as well as overarching societal influences like government, economy, culture, and demography.

To put such a conceptual assessment framework into action, an operational framework is also proposed by Briggs (8) to provide structure and organisation for the process and help with identifying stakeholders, defining the scope of the assessment and questions to be answered, selecting indicators, developing protocols, deciding on the methods of data analysis, defining a baseline or reference scenario, determining alternative scenarios that could be modelled, estimating and predicting health outcomes under alternative scenarios, and finally, communicating the findings to stakeholders.

Conceptual framework for IEHIA of leptospirosis in AS

The conceptual framework shown in Figure 2 was used to map out and explore the multiple exposure pathways and drivers for human leptospirosis infection in AS. The framework included general risk factors that were known to be important globally, as well as risk factors specific to the environmental conditions and cultural setting in AS. Potential risk factors were identified through a review of existing literature and refined after discussions with stakeholders, and these provided the basis for building the suite of indicators used for the assessment (see below).

Operational framework of the IEHIA of leptospirosis in AS

The operational framework shown in Figure 3 shows the overall design of the assessment and involved scoping the assessment, selecting the suite of indicators, sourcing and collecting data, analysing the data and building statistical models, producing sets of results, and identifying practical application of the findings. Each component of the assessment will be

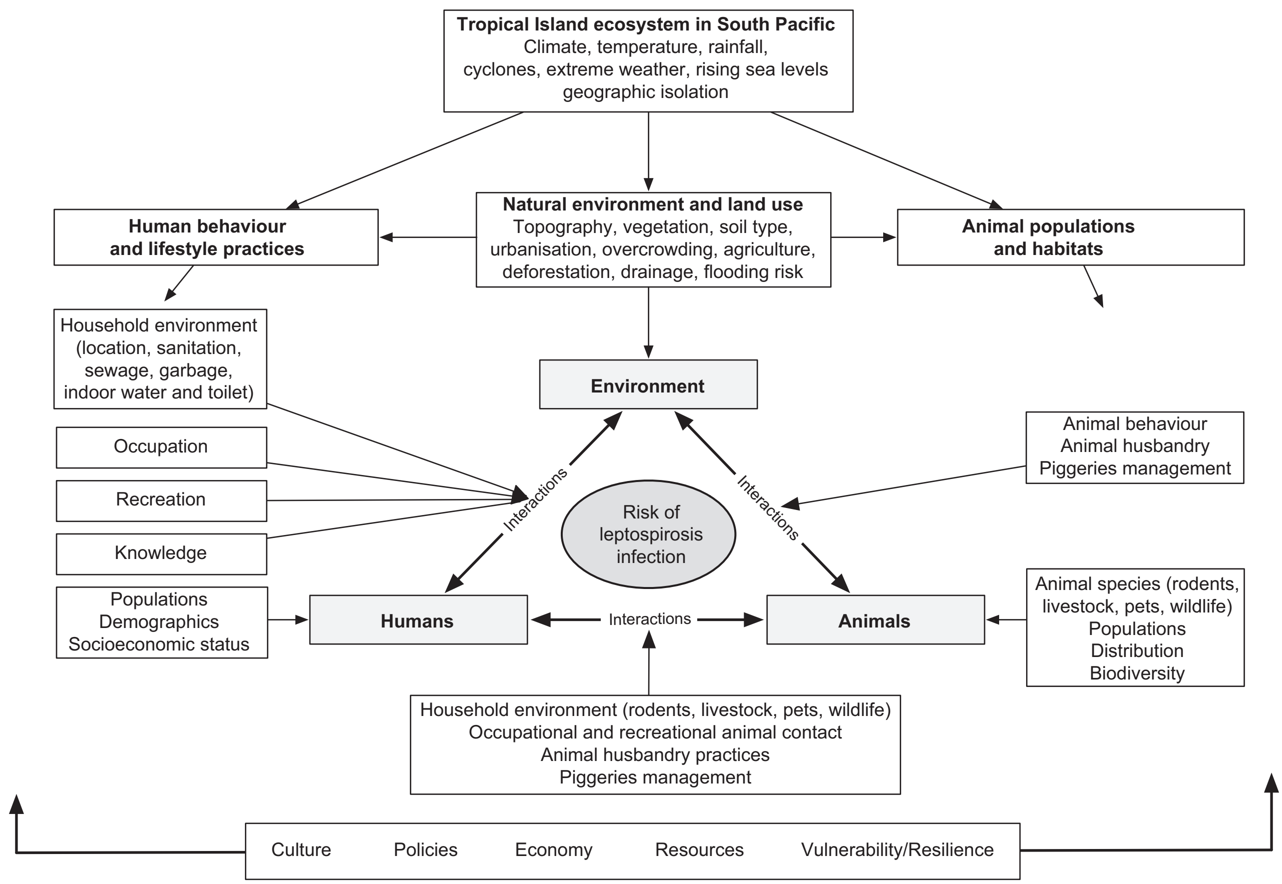

Figure 2 Conceptual framework for IEHIA of human leptospirosis in American Samoa.

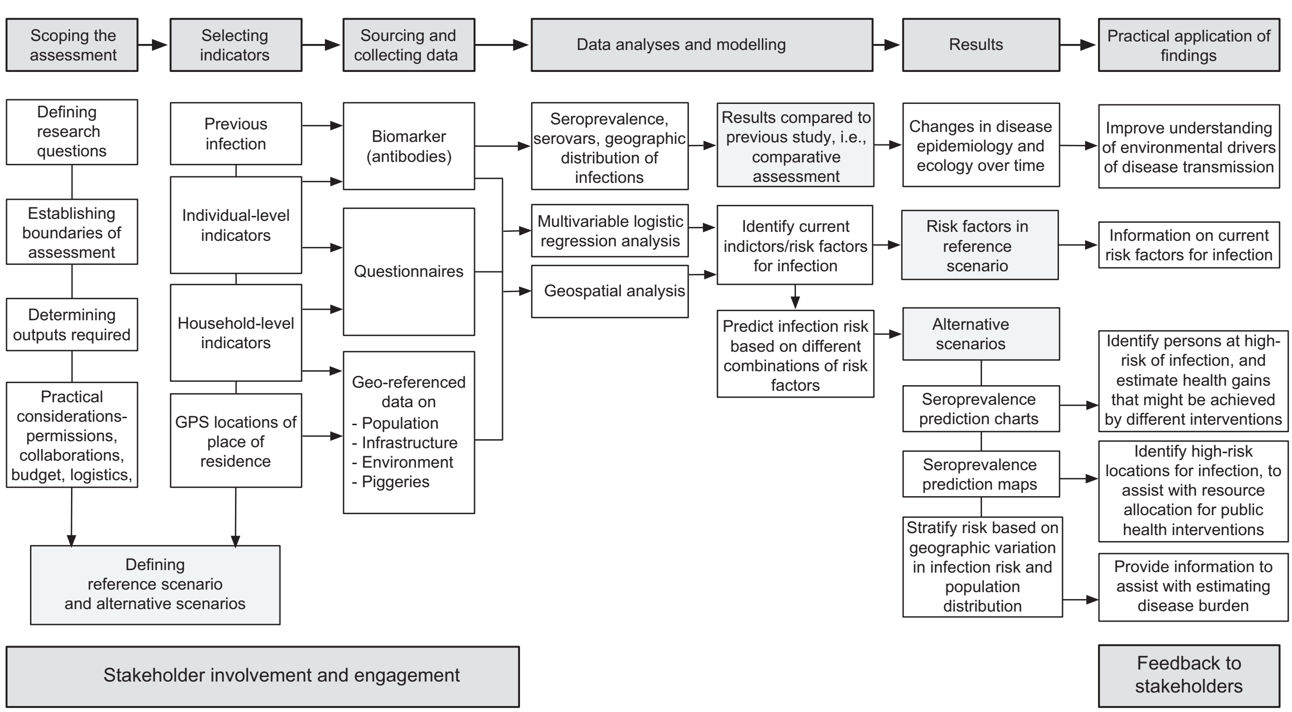

Figure 3 Operational framework for IEHIA of human leptospirosis in American Samoa.

described in detail below. As discussed earlier, stakeholders were involved and engaged throughout the assessment process.

Scoping the assessment and defining scenarios

Scoping the assessment provided limits within which the framework would operate. It involved defining the research questions, establishing the boundaries of the assessment, and determining outputs that need to be generated. The scope of the assessment determined the selection of indicators required to provide the appropriate and necessary data to measure the risk factors associated with the health outcome. A reference scenario was defined, and from there, health impacts resulting from alternative scenarios could be predicted.

In our case study of leptospirosis, the research questions were the following:

1. Have there been recent changes in the epidemiology of leptospirosis in AS, and what are the potential drivers of these changes? (Comparing findings with those of a previous study)
2. What is the current epidemiology of human leptospirosis in AS, and what are the risk factors for infection? (Reference scenario)
3. Could the above risk factors for infection be used to estimate the health impact under different conditions? (Prognostic alternative scenarios)

For this case study, the presence of *Leptospira* antibodies in study participants was used as the health outcome (or impact) measure. Antibodies are biomarkers of previous infection and would be detectable in clinical as well as subclinical cases. Seroprevalence (percentage of population with antibodies) was used as a measure of population-level health impact because it relates directly to the risk of infection. Risk factors for infection were measured using a suite of indictors (discussed below), and an epidemiologic approach was used to determine their current and potential future health impact. The assessment neither included a traditional risk assessment approach of quantifying the occurrence of the disease agent in the environmental media (water and soil) nor used a dose (of leptospires crossing into the body)-response (antibody development in individuals) approach to estimate infection risk. Leptospires are difficult to identify and quantify in the environment, and the dose-response approach is often not appropriate for infectious diseases because infectious agents (unlike toxins) are able to multiply within the human body at varying rates depending on the agent and the individual's immune status, i.e., a single organism might be sufficient to cause an infection or many organisms might fail to do so.

An IEHIA evaluates the current health impact status and uses it as the reference scenario, from which alternative scenarios could be developed to estimate the changes in health impact as risk factors change. The choice of alternative scenarios depends on research questions and the objectives of a study. In this case study, alternative scenarios consisted of combinations of indicators from the natural and household environment, individual KPB, proxy measures of flooding risk (altitude, soil type, vegetation type), populations of domestic pigs, and geographic location of the participants' households. To allow future estimations of beneficial health impact that might be gained through environmental health and public health interventions, alternative scenarios were constructed with those indicators that were potentially modifiable through such interventions.

Because of logistic constraints, the scope of the assessment only included adult humans and did not attempt to assess health impact in children or animals. The study was conducted in a tropical island ecosystem in the South Pacific, and findings might be relevant to other Pacific Islands with similar climate, lifestyle, culture, and animal species. However, it would be more difficult to generalise and apply findings to other high-risk epidemiologic settings for leptospirosis such as densely populated urban slums in developing countries (12).

Selecting indicators, sourcing, and collecting data

The selection of appropriate indicators was crucial because they formed the basis for the measurable parameters used in the study. The indicators needed to capture the full extent of risk factors and the multivariate nature of the exposure pathways, including the potential drivers and pressures in the local environment as well as human and animal behaviours and populations that could affect disease transmission. To ensure that the assessment was conducted in an efficient manner, it was also important to limit indicators to those that provide information within the scope of the assessment and consider the costs and logistics of data collection. The availability of preexisting data as well as the logistics and feasibility of collecting new data was also considered when scoping the study.

Before the final suite of indicators was compiled, several potential data sources in AS were explored, which included data on the epidemiology of leptospirosis in AS (e.g., data from disease surveillance, laboratories, health departments, hospitals); risk factors identified in previous studies, both in AS and elsewhere; population parameters (e.g., distribution, characteristics, behaviours census data); climate and environmental factors (e.g., government departments, research organisations, environmental agencies); and animal populations (e.g., environmental agencies, agricultural departments, research organisations).

The final suite of indicators, shown in Table 1, was broadly divided into four categories:

1. *Leptospira* antibodies – measured in blood samples collected from individual participants in the study and used as a biomarker of previous infection (the health impact measure)
2. Individual-level risk factors – a questionnaire was used to collect data on demographics and the individual's KPB that could influence the risk of infection.
3. Household-level risk factors – preexisting georeferenced environmental and animal data were used to measure potential sources of infection in the household environment

Table 1 Suite of indicators for IEHIA of human leptospirosis in American Samoa.

Health outcome measure	Considerations	Indicator	Data source
Presence of antibodies used as a biomarker of previous infection with leptospires	Seroprevalence used as the marker of population health impact	• Antibodies (biomarker)	Blood samples
Individual-level risk factors related to KPB	**Considerations**	**Indicator of personal risk factors**	**Data source**
Individual demographic parameters	Demographic disposition to exposure	• Age, gender, ethnic group, village of residence	Questionnaire
Socioeconomic status	Overcrowding, living conditions, standard of living	• Income • Number of people living in the house	Questionnaire
Occupation	Contact with leptospires (through animals, water, or soil) in the occupational environment	• Occupation • Indoor or outdoor work • Working with animals	Questionnaire
Knowledge about the disease	Potential to self-limit exposure to leptospires by avoiding high-risk behaviours and/or using personal protection (e.g., gloves, shoes)	• Heard of leptospirosis	Questionnaire
Contact with environmental carrier media – water and soil	Contact and therefore exposure to water and soil as potential carrier media for leptospires	• Flooding around or inside home or work place • Outdoor recreational activities (swimming, kayaking, fishing, hiking, camping, gardening, hunting, contact with mud) • Bathing in rivers/streams, contact with rain puddles • Growing vegetables or fruits at home	Questionnaire
Contact with potential animal reservoirs and their habitats	Contact with animals as potential sources of leptospires, as well as the potential for animal husbandry to attract rats (e.g., piggeries, chicken feed)	• Seen rats/mice around home • Contact with rats/mice • Raised pigs at home • Other animals in and around home (dogs, cats, chickens, bats) • Bitten by ticks or fleas	Questionnaire
Access to adequate sanitation	Personal and domestic hygiene	• Indoor toilet, indoor shower, piped hot water, garbage collection	Questionnaire
Household-level environmental risk factors	**Considerations**	**Georeferenced environmental indicators**	**Data source**
Housing density	Distribution and density of risk factors	• Number of other houses within various buffer distances from households	Environmental data
Characteristics of relevant environmental media at location of households	Characteristics of environmental media, i.e., drainage properties (flooding risk), soil acidity (suitability for leptospire survival), likelihood of exposure to water and soil	• Rainfall • Flood risk zones • Relative altitude of household in village • Proximity of streams • Vegetation type • Soil type	Environmental data
Backyard piggeries	Exposure to pig waste from backyard piggeries	• Location and density of piggeries in relation to households	Environmental data
Location of participants' households	**Considerations**	**Indicator**	**Data source**
GPS coordinates	Allows environmental data to be linked to place of residence	• GPS coordinates	Environmental data

through exposure pathways that are not specific to the individual's KPB
4. Geographic locations of households – Geographic Positioning System (GPS) coordinates were used to link georeferenced environmental data to each individual participant's place of residence.

Data analyses and modelling

Data analyses and the subsequent modelling involved a combination of analytical techniques to examine the diverse types of data on human parameters, animal populations, and the environment and consisted of

1. A comparative assessment of the findings of this study with results of a previous leptospirosis study conducted in AS.
2. Using multivariable logistic regression models and geospatial analysis to identify indicators that were significantly associated with the health impact (infection) and quantify the significance of the associations by determining the odds ratios of being infected when indicators were present. The findings provided an evidence base for the risk factors for leptospirosis infection in AS at the time of the assessment and were used to describe the reference scenario.
3. Using the models of the reference scenario as a platform, estimations of seroprevalence (measure of population-level health impact) were made for a number of alternative scenarios, which involved different combinations of risk factors.

Because the assessment was designed to produce practical information for public health interventions for leptospirosis, the alternative scenarios were presented as seroprevalence prediction charts and maps (see below).

Outputs

Comparative assessment

Leptospirosis seroprevalence, dominant serovars, and risk factors for infection from our assessment were compared with the results of a seroprevalence study conducted 6 years earlier in AS (19). The dominant serovars differed significantly between the two studies, and the emergence of new serovars were thought to be most likely the result of ecologic factors like changes in interactions between humans and the environment, introduction of serovars through transport of animals, changes in animal populations, and environmental change that favour the transmission of particular serovars (16).

Reference scenario

The details of the findings of the assessment have been described in earlier publications (20, 21). In summary, the assessment included 807 adults from 65 villages on five islands of AS. Antibodies indicating previous leptospirosis infection were found in 15.5% of participants, and logistic regression analysis was used to identify risk factors associated with the presence of antibodies. Table 2 shows the ten indicators of risk factors that were found to be significantly associated with previous infection and the odds ratios of being infected compared with participants without those risk factors. Six of these indicators were associated with individual-level risk factors (male gender, outdoor occupation/fish cleaners, income, lack

Table 2 Indicators and risk factors associated with the presence of *Leptospira* antibodies and used to define the reference scenario (20, 21).

Indicators	Risk factors for infection	Odds ratios of being infected	95% Confidence intervals
Gender[a]	Male (compared with female)	2.77	1.74–4.42
Occupation[a]	Outdoor workers and fish cleaners (compared with indoor workers)	2.77	1.40–5.49
Income[a]	Annual household income <US$10,000 (compared with >US$30,000)	2.74	1.05–7.11
Knowledge	Never heard of leptospirosis (compared with those who have)	0.6	0.38–0.96
Swimming at beach	Swimming more than once a week (compared with never going swimming)	2.01	1.23–3.26
Swimming or walking in rain puddles	Swimming or walking in rain puddles more than once a week (compared with never swimming or walking in rain puddles)	1.52	1.00–2.32
Fishing	Fishing more than once a week (compared with never having gone fishing)	1.78	1.11–2.83
Altitude of house[a]	Living below median altitude of village (compared with living above median altitude of village)	1.58	1.00–2.49
Vegetation type[a]	Living on agricultural land (compared with living in urban built-up areas)	2.09	1.12–3.89
Soil type[a]	Living on clay loam soil (compared with living on clay soil)	2.72	1.08–6.85
Density and location of piggeries[a]	Number of piggeries located within 250 m and higher than the participant's house	1.15[b]	1.05–1.26

[a]Statistically significant indicators on multivariable logistic regression. Other indicators are significant on univariate logistic regression analysis only. [b]Continuous variable: odds ratios reflects increase in risk for each extra piggery within 250 m and higher than the participant's house.

of knowledge about leptospirosis, swimming at the beach, swimming or walking in rain puddles, and fishing), and four indicators were associated with household-level environmental risk factors (the residence being below the median altitude of a village, being situated in agricultural areas, built on clay loam soils, and having higher density of piggeries located within 250 m and above the house).

Alternative scenarios

Using the logistic regression models developed in the reference scenario, estimations of seroprevalence (measure of population-level health impact) could be made for alternative scenarios that involved different combinations of indicators. The details of the methodology, goodness of fit of the models, and model validation statistics have been described in earlier publications (20, 21). The alternative scenarios explored in this assessment included the following:

1. Different combinations of significant risk factors associated with infection – used to produce seroprevalence (impact) prediction charts (Figure 4)
2. Different combinations of household-level environmental risk factors (based on geographic location) – used to produce a seroprevalence prediction map (Figure 5A)
3. Combining individual- and household-level risk factors – used to produce seroprevalence prediction maps for groups with different individual-level risk factors (Figure 5B and C)
4. Variations in population distribution across the island – used to estimate populations at risk based on population distribution and geographic variation in infection risk to assist with targeting interventions and resource allocation (Figure 6)

The seroprevalence prediction charts in Figure 4 show the combined effects of indicators in determining overall infection risk and provide a more accurate estimate of seroprevalence than individual indicators or a simple count of the number of indicators. The four variables used for the chart in Figure 4A were chosen because they were likely to be of practical use to (i) assist clinicians with identifying individuals at risk of infection, particularly when laboratory diagnosis is not readily available, and (ii) show potential gains in beneficial health impact that might be achieved by implementing different public health interventions (e.g., promoting occupational safety, increasing public awareness of disease, or improving piggery management) (20). Figure 4B shows how different types of environmental change could influence the risk of infection (e.g., urbanisation, expansion of agricultural activity, increase in the number of piggeries). Altitude and soil types provide indirect measures of flooding risk and illustrate the importance of improving drainage as well as the potential increase in infection risk with climate change and the predicted increase in flooding in the Pacific Islands (21). The charts therefore provide estimates not only of the current seroprevalence status but also of the changes in future seroprevalence that might occur with alternative scenarios, either through public health interventions or environmental change.

The maps in Figure 5 show a significant geographic variation in health impact, and the maps in Figure 5B and C show how this variation in risk is further modified by individual-level indicators (21). The ability to accurately identify and map high-risk areas for infections could assist public health authorities to target more specific environmental sources of infection and assist in planning and implementation of interventions.

The graph in Figure 6 provides additional information for assessing potential health impact by estimating the number of households exposed to different levels of health impact as well as the number of houses that were located in actual high-risk areas.

Practical application of the findings

This assessment identified important individual- and household-level risk factors for leptospirosis infection in the target population and provided an evidence base for potential public health interventions. At the individual level, recommendations for interventions included the use of protective clothing, gloves and shoes during high-risk activities like outdoor work, and improving knowledge about leptospirosis. At the community level, improving the management of piggeries and waste drainage could reduce environmental contamination. Improving drainage and waste management in villages could reduce flooding risk and thereby also reduce exposure to leptospires. At a regional level, leptospirosis is a significant health problem in other similar environments, and findings from this assessment might also provide insight into the risk factors for disease transmission in such areas. The combination of climate change, population growth, and urbanisation in the Pacific region could potentially result in an upsurge in leptospirosis incidence, and the potential increase in disease burden could be controlled by appropriate and timely public health interventions (20, 21).

At the population level, the assessment produced practical information to identify high-risk populations and geographic variations in seroprevalence. The seroprevalence prediction charts and maps demonstrated how multiple risk factors (demographic, behavioural, animal, environmental) combined to drive overall infection risk and highlighted the importance of a multicriteria approach to understanding public health interventions for leptospirosis control. The charts and maps visually presented complex data in formats that are more easily understood and interpreted, so that the information could be more readily applied to inform intervention strategies.

Estimating the shifts in seroprevalence based on alternative scenarios helped to estimate future health impact based on hypothetical changes in human population (demographics, distribution, knowledge, occupations), animal populations (numbers and locations of piggeries), and flooding risk (land use, agriculture, urbanisation). For example, the first seroprevalence prediction chart (Figure 4A) could be used to assess and compare potential health benefits achievable by different types of interventions (e.g., managing piggeries vs. improving occupational health and safety for high-risk groups vs. a public education campaign about leptospirosis). This information

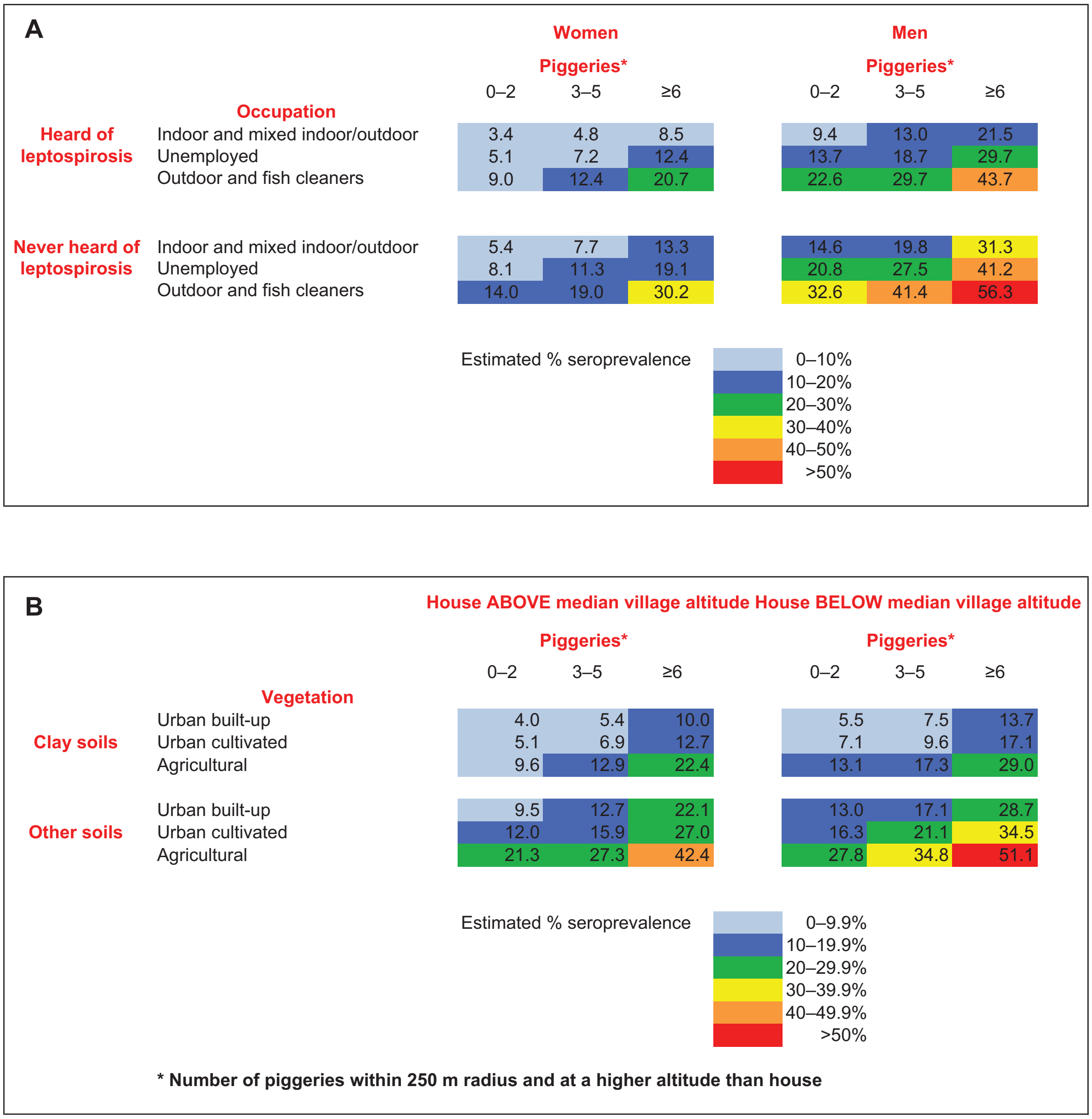

Figure 4 Seroprevalence prediction charts [reproduced from (20) and (21)]. The numbers in each coloured cell represent the estimated seroprevalance based on four indicators. (A) Based on gender, occupation, knowledge, and piggeries around the home. (B) Based on four household-level environmental indicators: altitude, density of piggeries around the home, soil type, and vegetation type.

could help direct public health intervention strategies and ultimately lead to optimising cost-effectiveness as well as social cost-benefit of different interventions to reduce health impact. The assessment also showed that basic environmental indicators could be used to identify high-risk locations for leptospirosis infection (Figure 5) and supported a novel approach of using environmental monitoring to enhance infectious disease surveillance (22) and improve the overall effectiveness of environmental health surveillance and management (21).

Discussion

The process of an IEHIA has been proposed for the assessment of complex situations involving multiple hazards or disease agents, resulting in multiple risks and exposure pathways, and multiple health outcomes (8, 9). The integrated approach described in this article was shown to provide direct, comprehensive, and strategic information on the health impact of an environmental hazard, which could be used to inform intervention strategies. This approach demonstrated that an IEHIA approach is also applicable and valuable for simpler assessments involving single infectious disease agents and associated health outcomes.

Rather than the traditional risk assessment approach of measuring exposure to known quantities of a disease agent in the environment, this case study applied the IEHIA approach to investigate an infectious disease by combining measurement of biomarkers of infection with an epidemiologic assessment, using a suite of risk factor indicators to provide

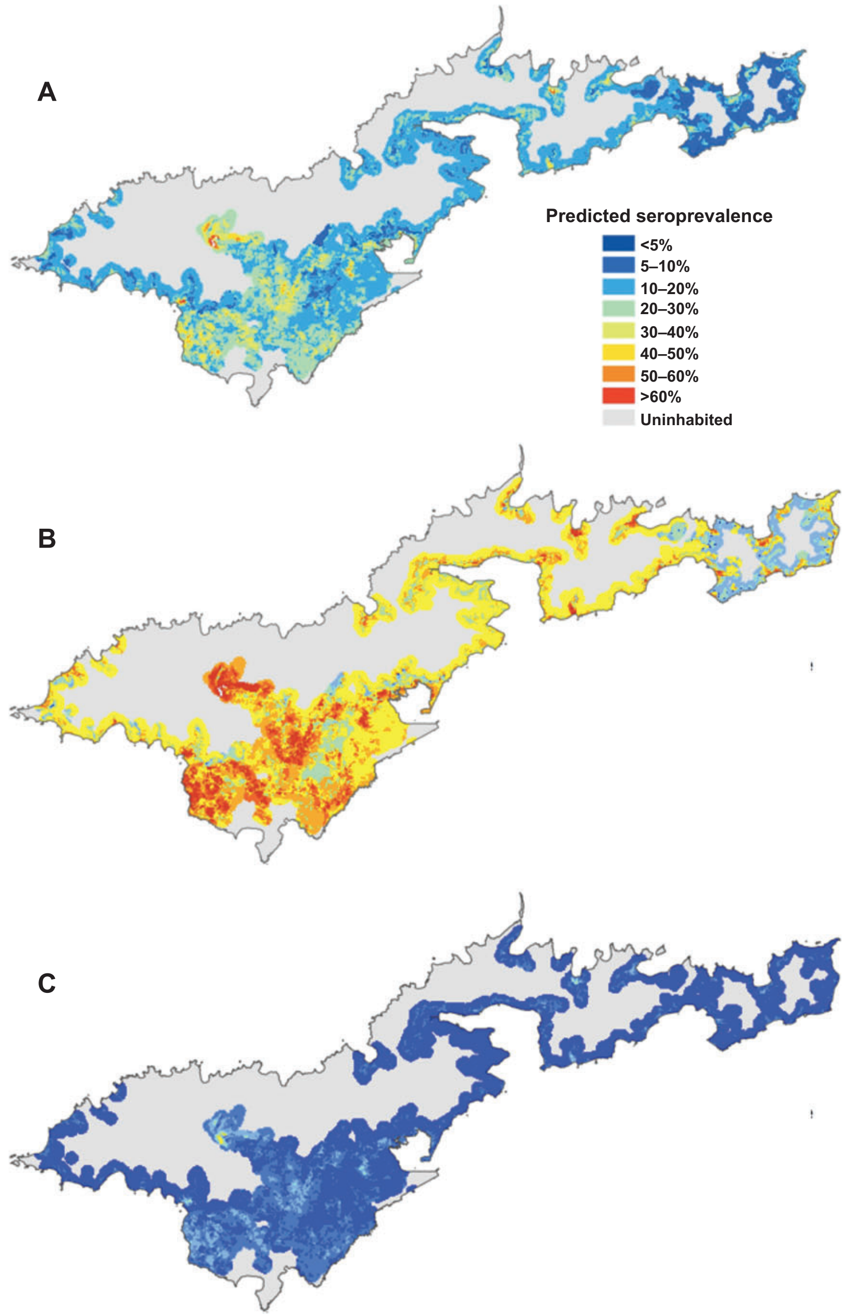

Figure 5 Seroprevalence prediction maps [reproduced from (21)]. (A) Based on four environmental indicators (altitude, piggeries, vegetation, and soil type). (B) is based on four environmental indicators plus high-risk individual indicators (male, outdoor worker, and no knowledge of leptospirosis). (C) Based on four environmental indicators plus low-risk individual indicators (female, indoor worker, and knowledge of leptospirosis).

quantitative estimates of current and future health impacts of leptospirosis, as well as demonstrate the prognostic strength of such an integrated approach.

With conventional environmental exposure or health risk assessments of an infectious disease, the ability to accurately quantify the risk of infection is limited because multiple potential exposure pathways and the paucity of reliable dose-response data combine to produce large margins of error and uncertainties. Even if the risk of exposure could be accurately quantified, risk assessments often do not provide sufficient information on the likelihood of exposure, the odds of being infected, or any subsequent health impact. The lack of quantitative measures of health impact would also make it more difficult to model and predict improvements in beneficial health impact that might be gained from environmental health and public health interventions.

Finally, it must be pointed out that there were limitations to the case study presented here. The scope of the assessment

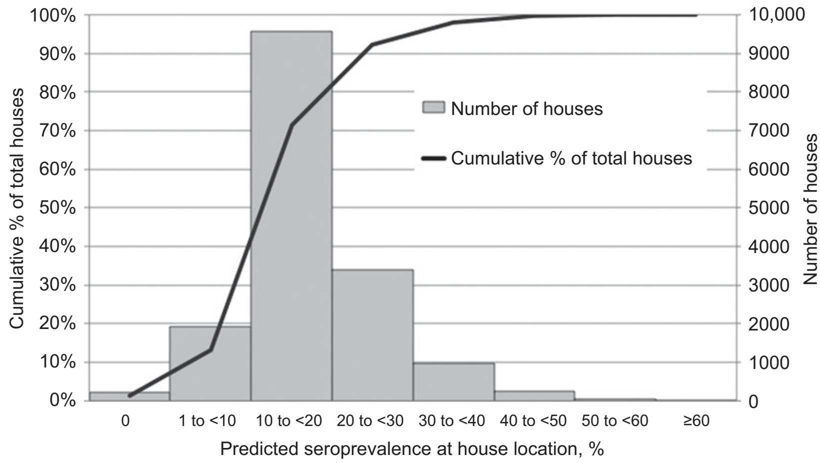

Figure 6 Estimates of population at risk based on geographic variation in population distribution and the seroprevalence prediction map in Figure 5A [reproduced from (21)].

did not include all possible risk factors, exposure pathways, or population groups at risk. The ability to develop and explore alternative scenarios depended heavily on the availability of preexisting data as well as the capacity and feasibility of collecting new data. Future assessments could improve the accuracy of estimates by identifying additional indicators and exploring other alternative scenarios. For example, potentially important alternative scenarios that were not investigated included the effect of seasons, climate, and extreme weather events; the risk factors for infection in children; and the role that other animal species play in disease transmission.

Conclusion

This article demonstrated the strength of a practical and prognostic application of an IEHIA. The range of methods applied in the process is not new and neither are they unique. However, we have shown that the integration of the methods improved the ability to quantify the associations between an environmental hazard and a health outcome, taking into account the multiple exposure pathways, population parameters, and socioeconomic factors that could modify the health outcome.

Conflict of interest statement

The authors do not have any conflicts of interest to declare.

References

1. Prüss-Üstün A, Corvalán C. Preventing disease through healthy environments: Towards an estimate of the environmental burden of disease. Available at: http://www.who.int/quantifying_ehimpacts/publications/preventingdisease/en/index.html. Accessed on 7 July 2012.
2. Mindell JS, Boltong A, Forde I. A review of health impact assessment frameworks. Public Health 2008;122:1177–87.
3. Veerman JL, Barendregt JJ, Mackenbach JP. Quantitative health impact assessment: current practice and future directions. J Epidemiol Community Health 2005;59:361–70.
4. Lhachimi SK, Nusselder WJ, Boshuizen HC, Mackenbach JP. Standard tool for quantification in health impact assessment a review. Am J Prev Med 2010;38:78–84.
5. World Health Organization. Quantifying environmental health impacts. Available at: http://www.who.int/quantifying_ehimpacts/en/. Accessed on 7 July 2012.
6. Bhatia R, Seto E. Quantitative estimation in health impact assessment: opportunities and challenges. Environ Impact Assess Rev 2011;31:301–9.
7. Cameron D, Jones IG. John Snow, the Broad Street pump and modern epidemiology. Int J Epidemiol 1983;12:393–6.
8. Briggs DJ. A framework for integrated environmental health impact assessment of systemic risks. Environ Health 2008; 7:61.
9. Knol AB, Briggs DJ, Lebret E. Assessment of complex environmental health problems: framing the structures and structuring the frameworks. Sci Total Environ 2010;408:2785–94.
10. Cameron J, Jagals P, Hunter PR, Pedley S, Pond K. Economic assessments of small-scale drinking-water interventions in pursuit of MDG target 7C. Sci Total Environ 2011;410–1: 8–15.
11. World Organisation for Animal Health. One health. Available at: http://www.oie.int/en/for-the-media/onehealth/. Accessed on 7 July 2012.
12. Lau CL, Smythe LD, Craig SB, Weinstein P. Climate change, flooding, urbanisation and leptospirosis: fuelling the fire? Trans R Soc Trop Med Hyg 2010;104:631–8.
13. Lau C, Smythe L, Weinstein P. Leptospirosis: an emerging disease in travellers. Trav Med Infect Dis 2010;8:33–9.
14. Tulsiani SM, Lau CL, Graham GC, Van Den Hurk AF, Jansen CC, et al. Emerging tropical diseases in Australia. Part 1. Leptospirosis. Ann Trop Med Parasitol 2010;104:543–56.
15. Derne BT, Fearnley EJ, Lau CL, Paynter S, Weinstein P. Biodiversity and leptospirosis risk: a case of pathogen regulation? Med Hypotheses 2011;77:339–44.
16. Lau CL, Skelly C, Smythe LD, Craig SB, Weinstein P. Emergence of new leptospiral serovars in American Samoa – ascertainment or ecological change? BMC Infect Dis 2012;12:19.

17. World Health Organization. Human leptospirosis: guidance for diagnosis, surveillance and control. Available at: http://whqlibdoc.who.int/hq/2003/WHO_CDS_CSR_EPH_2002.23.pdf. Accessed on 7 July 2012.
18. World Health Organization. Report of the Second Meeting of the Leptospirosis Burden Epidemiology Reference Group. Available at: http://whqlibdoc.who.int/publications/2011/9789241501521_eng.pdf. Accessed on 7 July 2012.
19. Winger K. Leptospirosis: a seroprevalence survey on American Samoa. Available at: http://www.botany.hawaii.edu/basch/uhnpscesu/pdfs/sam/Winger2004AS.pdf. Accessed on 7 July 2012.
20. Lau CL, Dobson AJ, Smythe LD, Fearnley EJ, Skelly C, et al. Leptospirosis in American Samoa 2010: epidemiology, environmental drivers, and the management of emergence. Am J Trop Med Hyg 2012;86:309–19.
21. Lau CL, Clements AC, Skelly C, Dobson AJ, Smythe LD, et al. Leptospirosis in American Samoa – estimating and mapping risk using environmental data. PLoS Negl Trop Dis 2012;6:e1669.
22. Carver S, Kilpatrick AM, Kuenzi A, Douglass R, Ostfeld RS, et al. Environmental monitoring to enhance comprehension and control of infectious diseases. J Environ Monit 2010;12:2048–55.