CHAPTER 13

Waterborne zoonoses and changes in hydrologic response due to watershed development

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Abstract

Hawaii’s mountain-to-sea ecosystems provide unique opportunities to evaluate watershed-scale processes. In this chapter, we use a watershed on Oahu, Hawaii (Manoa Stream) to explore the link between watershed development, hydrologic response and increased risk of waterborne disease as a result of flooding and the presence of commensal rodents chronically infected with leptospirosis. Flooding from the watershed in 2004 led to an outbreak of leptospirosis among people exposed to flood waters during clean-up efforts. We present hydrologic analysis of a flood-producing storm and animal sampling results to illustrate the hypothesis that watershed development may increase the likelihood of flooding and the magnitude of sources of pathogenic microbes that could be mobilized during flood-producing rainfall. The analysis considers land-use changes in the Manoa stream watershed that took place between 1939 and 2005.

Hydrologic response to the type of rain storm observed in 2004 has changed significantly since 1939. Peak flow rates would have been approximately 180% lower in 1939 than those observed during the 2004 floods. Rodent trapping results indicate that 27/354 rodents trapped over the course of 14 years were infected with serovars of Leptospira. When carried out intensively, trapping results suggest a low (~6%) but consistent prevalence of infection with serovars found in confirmed cases of leptospirosis following the 2004 flood. We discuss these results in the context of conditions likely to lead to an outbreak of waterborne disease, and how the likelihood may increase in areas experiencing urban expansion and high-density residential growth.
1 Introduction

A strong link exists between extreme weather events, flooding and the outbreak of zoonotic diseases caused by microbial pathogens [1]. Illness results in part from exposure to microbial contaminants in flood waters [2]. Flooding is likely to create an extra burden of microbial contaminants by disrupting human-sewage-treatment facilities and by mobilizing pathogens that are resident in soils and animal populations, increasing the likelihood that people will be exposed to them.

Flooding is most often caused by extreme weather events, such as cyclones and hurricanes [2]. These are considered to be rare and unusual, especially in the case of very destructive and disruptive flooding. Anthropogenic changes in landscape may increase the likelihood of flooding [3, 4].

Figure 1: Illustration of hypothetical effects of watershed development on risk of infectious disease outbreaks from exposure to waterborne pathogens. Under predevelopment conditions, watershed response to storms is attenuated by abstraction losses in vegetated canopies and infiltration into soils. Resultant streamflow hydrographs caused by equivalent storms (center) have slower times to peak, and smaller quantities of peak flow and volume of storm flow than those observed postdevelopment. At the same time, commensal animal populations that are maintenance hosts for waterborne parasites may increase as food sources and habitat are introduced with development. Regardless of changes in prevalence, the magnitude of the source of pathogenic microbes in the watershed may also increase. At the same time numbers of downstream people increase with development as the risk of flooding also increases, because of changes in hydrologic response in the watershed.
Land-use changes may be an immediate cause for concern with respect to zoonotic diseases and transmission to susceptible populations by flooding. As discussed by Kaneshiro et al. [5], residential and commercial development in watersheds may synergistically increase the potential for waterborne, zoonotic diseases to emerge or re-emerge, in part as a consequence of change in factors that affect hydrologic response (Fig. 1). Kaneshiro et al. [5] propose that development of watersheds may create habitat and food sources for maintenance populations of zoonotic diseases and, concurrently, increase transport and exposure potential by changing watershed response to flood-producing rainfall.

Watershed development adds impervious surface to watersheds and can change hydrologic response because of several factors. These include a decrease of abstraction losses during storms because of loss of absorbing surfaces in watersheds (for example, vegetation and soil), increase in runoff volume because of added impervious surfaces (streets, parking lots and rooftops) and a decrease in the hydrologic response time to runoff-producing precipitation due to extensive networks of storm-water-management infrastructure, including conduits and paved portions of stream channels.

Emerging infectious diseases generally have increased globally in association with urbanization, agricultural intensification, and habitat alteration [1, 6, 7]. Emerging and re-emerging infectious diseases have been discussed in the context of environmental change, particularly with respect to anticipated effects of global warming [8, 9]. This may be the result of increased contact between individuals within host animal populations via specific media, such as contaminated water. Several factors may contribute to this, including habitat loss, alteration or creation [9, 10] and increased contact between host populations and human populations, especially at the margins of and within newly developed areas [11].

Several recent reviews suggest that zoonoses, transmitted from animal hosts to humans by a variety of routes of exposure, are an emerging class of disease that will affect greater numbers of people as a consequence of population growth, urbanization and climate change [12–14]. Wastes from infected hosts, including feces and urine, may contain disease-causing microbial agents, which may be transported by flowing water away from where wastes are deposited. Environmentally transmissive forms of microbial pathogens may survive environmental stresses and infect humans. For example, oocysts of the parasitic protozoa *Cryptosporidium parvum* remain infective for days to months while in suspension in aqueous solution [15, 16], fecal suspensions [17] and in soils and stored animal wastes [18]. *Cryptosporidium, Giardia, Microsporidia* and *Toxoplasma* have been the causative agents of recent waterborne-disease outbreaks in developed nations [14].

Leptospirosis is considered to be a re-emerging disease [19] that infects people by contact with contaminated water, soil and the urine of infected animal hosts [20]. The disease is commonly associated with flooding [20–24] and is prevalent in flood-prone areas [25]. Leptospirosis is caused by *Leptospira interrogans* spirochetes. Infection may result from contact with contaminated water or urine from infected animals, especially through skin abrasions and the mucosa. Symptoms of illness range from mild febrile reactions to sometimes fatal disease. Leptospirosis is
thought to be substantially underreported, because symptoms are easily confused with those associated with common influenza, dengue fever and other viral infections. The incidence of disease among humans has a marked association with seasonal weather trends; for example, the number of new cases in regions with endemic leptospirosis increased during wet months [26, 27]. Researchers also have noted that the incidence of leptospirosis in host animal populations coincides directly with seasonal fluctuations in rainfall [28–30].

A recent review paper suggested that leptospirosis be considered as a model zoonosis for evaluating the link between ecosystem change and disease emergence, especially related to the influence that potential reservoir hosts may have on susceptible human populations [31]. Other authors have suggested that Hawaii’s islands offer ideal sites for case studies to understand anthropogenic influences on watershed processes, in part because watersheds can be viewed as scale models of large continental mountain-to-sea ecosystems [5]. The suggestion acknowledges the influence of Hawaii’s topography on hydrologic processes. Hawaii’s islands have topographic relief sufficient to create significant orographic effects. Many of the islands have distinct windward/leeward topographic divides that define trends in precipitation distribution. Orographic effects lead to very large differences in rainfall over short distances. For example, on Oahu, the average annual rainfall estimated from 30 years of record at the Lyon Arboretum, in Manoa Valley (152 m (500 ft) AMSL), is 3886 mm (153 in). Average annual rainfall at the University of Hawaii rainfall gaging station (24 m (80 ft) AMSL), approximately 3.1 km (1.9 mi) south southwest of the Lyon Arboretum gage, is 1016 mm (40 in), based on 54 years of observation (www.wrcc.dri.edu/Climsum.html, last accessed 7/2006).

In the steep valleys that fall away from both the leeward and windward sides of topographic divides, such as the Ko’olau range on Oahu (Fig. 2), storms may be of moderate duration (hours) but high intensity (mm (in)/hr). As a consequence, the relationship between changes in land use and various aspects of hydrologic response, including water quality, should be readily discernible in modeling analysis and long-term measurements of the physical system. In the case of the latter, the violence of occasional floods has disrupted data-collection efforts in several locations, including Manoa Stream. However, modeling approaches remain feasible, and can be supported by historical aerial photographic records, land-use analyses and maps and databases related to the physical characteristics of watersheds, including soils and topography.

In this chapter, we examine the change in hydrologic regime in a specific location in Hawaii that experienced unusual, destructive flooding in 2004 and confirmed and suspected cases of leptospirosis among people exposed to flood waters during clean-up efforts. We focus on leptospirosis as an example of a pathogen associated with commensal animal populations that may increase in numbers as watersheds are developed. We estimate changes in hydrologic response due to changes in watershed use over a 65-year period, with animal-sampling results to illustrate a hypothesis presented by Kaneshiro et al. [5] (Fig. 1). The data are drawn from several sources and applied to the Manoa Stream watershed on Oahu, Hawaii, but suggest that watershed development was a factor that led to flooding and also to a small outbreak of this zoonotic, waterborne disease.
1.1 Physical setting

1.1.1 The Manoa Stream watershed

The Manoa Stream watershed, on the island of Oahu, Hawaii (Fig. 2) has a total relief of approximately 945 m (3100 ft) from the uppermost portion of the watershed to a gaging station operated by the U.S. Geological Survey at Kanewai Field (gaging station number 16242500), located on the southeastern portion of the University of Hawaii, Manoa campus (Fig. 3). The average annual rainfall recorded at a gage in the upper reaches of the watershed is 3 886 mm (153 in), based on thirty years of record (1975–2005, see http://www.wrcc.dri.edu/summary/Climsmhi.html (Manoa Lyon Arboretum, last accessed 6/06)). Average annual streamflow reported for gaging station 16242500 ranged from 0.2–0.3 m$^3$/s (7–11 ft$^3$/s) in 2000–2003. The perennial stream rises from the confluence of three primary tributaries at the base of extremely steep headwalls formed by the Ko’olau range. The stream course of 7.1 km (4.4 mi) drains an area of 14.2 km$^2$ (5.5 mi$^2$). The stream course is posted with signs warning of the risk of contracting leptospirosis from contact with stream water, from the base of Manoa Falls (accessible by foot only), and at almost every bridge crossing and access point along its course to the confluence with the Palolo Stream, downstream of gaging station number 16242500.

Figure 2: Study area (watershed boundaries shown within white box), Manoa Stream island on Oahu, Hawaii. The Ko’olau range trends from the northwest to the southeast on the eastern half of the island and causes significant precipitation gradients, including Mania Valley.
Figure 3: Photomosaics of land uses, 1939 (left, from Hawaii State Archives) and 2005 (right, from Google Earth®), with overlay of watershed bounds for Manoa Stream (black line). In 2005 nearly all land in the watershed with a slope of less than 22° was developed, while in 1939, most of the land was used for small-plot agriculture or covered in dense tropical forest.

Figure 4: Manoa Stream watershed (right panel, outlined in blue), showing animal sampling points (red: collected animal positive for serovar ballum; yellow: positive for serovar icterohemorragiae; blue: positive for mixed serovars; black: negative results), and (left panel) detail of flood path (blue arrows) through University of Hawaii campus, with flood-damaged buildings depicted in red.

The watershed, with an overall area-weighted average slope of 22°, has two features that are common in the Hawaiian islands: (a) watershed relief is extreme, and (b) substantial portions of drainage areas are comprised of fractured volcanic rock formations with relatively thin soil covers. The latter feature is important with
respect to hydrologic response. During dry periods dense canopies and thin soil covers with underlying fracture networks are thought to be the cause of initial abstraction losses during the early stages of storms [32]. However, soils and fracture networks are often saturated during periods of prolonged rain, which commonly occur from October through March (www.wrcc.dri.edu/narratives/HAWAII.htm, last accessed 4/06). Saturated soils accentuate watershed response to storms, especially the quantity of peak discharge and the time to peak discharge rates from the onset of storms [32].

The watershed has evolved from a largely undeveloped agricultural valley in the early part of the 20th century to a heavily developed residential and commercial area in the early part of the 21st century (Fig. 3). Land uses in the watershed are predominantly residential, with some open space (park lands, school yards and a cemetery) and commercial areas. The upper margins of the watershed are largely undeveloped. Much of the intensive building took place in the last quarter of the 20th century. Although the pace of development has slowed significantly, subdivision and new construction continue throughout the valley.

1.1.2 Manoa Stream flood, 2004
On October 30th, 2004 Manoa Stream swelled far beyond channel capacity at the Woodlawn Bridge (constructed in 1975), forcing debris- and sediment-filled waters into an adjacent subwatershed that contained a majority of the University of Hawaii, Manoa’s buildings and facilities (Fig. 4). The rectangular opening in the stream channel defined by the Woodlawn bridge was designed to convey approximately 235 m$^3$/s (8300 ft$^3$/s). However, accumulated woody debris and sediment from upstream erosion and bank collapse reduced the capacity to carry flood waters. Flooding led to extensive damage of research, administrative and academic facilities in a swath across the campus (Fig. 4). In all, the flood damaged 32 buildings, 25 of which were sited and constructed before 1980. The flooding was especially destructive for researchers and librarians, who lost active experiments and digital and paper records. The flooding left standing water and sediment throughout affected areas, including inside buildings.

2 Methods

2.1 Estimated changes in hydrologic response associated with changes in land use

We carried out this analysis to evaluate the effects of increased proportion of impervious surface in the watershed during the past seven decades. We estimated the change in hydrologic response using the curve-number approach to predict peak discharge rates from observed rainfall amounts [33, 34]. We developed an area-weighted representation of key aspects of the watershed at four periods (1939, 1955, 1976 and 2005) using land-use and land-cover data and soil characteristics, as described below. The storm used for analysis was drawn from the National Oceanic and Atmospheric Agency’s report of the 2004 Manoa Valley flood
Rain gages in the northeastern head of the valley recorded a cumulative total of 221 mm (8.7 in) of rain in six hours (ibid.). For the analysis, we assumed a storm duration of six hours and storm total of 221 mm (8.7 in). This duration and intensity of storm were estimated to have a 2% probability of occurring in a given year (ibid.). This is similar to the storm that caused flooding on Oahu in 1988 (51–102 mm/hr (2–4 in/hr) for 5–6 h [32]).

Excess rainfall was transformed to storm hydrographs using a dimensionless unit hydrograph and watershed physical characteristics (average slope, watershed area and watershed length [33]). The analysis relied on the following series of equations to derive time to peak and peak discharge.

\[ t_p = \frac{AD}{2} + L, \]
\[ L = \frac{0.00526(0.8)\left(S+1\right)^{0.7}}{\sqrt{Y}}, \]
\[ S = \frac{1000}{CN} - 10, \]
\[ q_p = \frac{484AQ}{\left(\Delta D/2\right) + L}, \]
\[ Q = \frac{(P - 0.25)^2}{(P + 0.85)}. \]

In these equations, \( t_p \) is the time to peak discharge (h), \( D \) is the duration of runoff-producing rainfall (h), \( L \) is the lag time (h) between the onset of runoff-producing rainfall and peak discharge rate, \( l \) is the hydraulic length of the watershed (ft), \( Y \) is the average slope of the watershed (ft/ft), \( CN \) is the curve number value typical of a combination of soil hydrologic group and land use, \( A \) is watershed area (square miles), \( Q \) is excess precipitation (inches, determined using the curve-number approach, eqn. (5)), and \( P \) is total storm precipitation (in). Application of these equations for simulation assumes uniform distribution of rainfall throughout a watershed. The average annual rainfall gradient between the head of Manoa Valley (at the Lyon Arboretum) and a rainfall gage in the lower portion of the stream course is approximately 2362 mm (93 in)/3.1 km (1.9 mi). For this storm the rainfall gradient was approximately 188.0 mm (7.4 in)/3.1 km (1.9 mi) (280.7 mm (11.1 in) at the head of Manoa Valley versus 61.0 mm (2.4 in) at the University of Hawaii’s Experimental Farm [35]. However, simulations of peak flow rates recorded at a gaging station defined as the outlet of the watershed for these analyses corresponded well with observed annual peaks flows (see below), suggesting that the heterogeneous distribution of rainfall did not excessively violate the assumptions inherent in simulations.
Land uses in 1939 (Fig. 3), 1955, 1976 and 2005 were determined from aerial photographs obtained from the Hawaiian State Archives (1939, 1955), a land-use and land-cover analysis completed by the Earth Resource Observation and Science division of the U.S Geological Survey (1976) and satellite images obtained from Google Earth® v. 3.0.0762 (acquired in 2005). All digital files referenced NAD83, UTM zone 4N. Land-use and land-cover designations were based on the classification system proposed by Anderson et al. [36], for Level II analysis. Scanned aerial photos and satellite images were rectified to a digital line graph version of the 1: 24,000 Honolulu quadrangle, using the Global Mapper® v. 7.01 image-processing and analysis program.

Estimates of area-weighted curve numbers to represent the watershed during each selected year were derived from land-use/land-cover data and soil characteristics. The geographic information system Idrisi Kilimanjaro v. 14.01 was used for watershed delineation, digitizing land uses for the 1939, 1955 and 2005 data sets and developing a crosstabulation matrix with interpreted Soil Survey Geographic Database (SSURGO) soil types (land-use type x soil hydrologic group). Results of crosstabulations were used to develop area-weighted average curve numbers for the entire watershed for each year.

We evaluated area-weighted curve-number estimates for current conditions by comparing reported annual peak flows (see http://nwis.waterdata.usgs.gov/hi/nwis/peak/?site_no=16242500, last accessed 4/06) for 1999, 2001, 2002 and 2004. These flood peaks were selected for comparison because each occurred after periods of prolonged rainfall, which presumably led to saturated soils and approximately equivalent abstraction losses when peak rainfall occurred. Durations and intensities for these storms, reported by the National Oceanic and Atmospheric Administration’s archived storm data for the upper portion of the watershed (see http://www.prh.noaa.gov/hnl/hydro/hydronet/hydronet-data.php (last accessed 4/06)) ranged from 1.5–5.25 h, with precipitation intensities of 60.2 mm (2.4 in)/1.5–224.3 mm (8.8 in)/5.25 h. The area-weighted curve-number estimate for this time period appeared to be an appropriate representation of the watershed under current conditions, with observed and estimated peak discharge rates correlated at 0.99.


The Hawaii Department of Health’s (HDOH) Vector Control Branch (VCB) has statewide responsibilities to control disease outbreaks and monitor insect vectors and zoonotic diseases. The VCB traps rodents for several reasons, including requests from the Disease Investigation Division of HDOH related to potential exposure sites in human cases of leptospirosis or murine typhus, complaints of excessive rodent activity in an area, and special studies with intensive neighborhood surveillance.

Investigators select sites according to the reasons for trapping. In the case of sites of potential human exposure or in response to complaints, trap sites are specified by an investigator from the Disease Investigation Division or by the complainant and a limited number of traps is set. For intensive neighborhood surveillance, the VCB
traps at multiple sites in a single neighborhood. Each trapping site is equipped with several rat traps and one mongoose and one mouse trap. Traps used include turtle-back cages for rats, ‘tin cat’ multiple catch traps for mice and Havahart wire cage traps for mongooses. Trapped animals were transported from the field to the HDOH’s Zoonoses Laboratory and euthanized using carbon dioxide. Only live-trapped animals were tested.

To obtain the results reported in Table 2, kidneys were aseptically removed from animals and cultured for pathogenic leptospires. Sera from rats and mongooses were not tested for leptospiral antibodies. The results of serological surveys of rodent populations differ from those obtained by culturing kidney tissues, in part because colonized kidney tubules do not stimulate an immune response [37]. Accordingly, the VDC used cultures from kidneys to determine if trapped rodents were infected, using the microscopic agglutination test [38]. One antiserum from each of six or seven serogroups was allowed to react with the unknown isolate to attempt to place it in a serogroup.

3 Results

3.1 Peak-flow estimates

Table 1 presents, for each year considered, estimated flood characteristics associated with the design storm used for analysis. Figure 5 presents estimated hydrographs for each simulation. Table 1 and Fig. 5 indicate that hydrologic response to a storm equivalent to the October 2004 storm changed significantly with changes in land use. Watershed response was compressed and substantially increased. Estimated peak discharge rates increased by approximately 183% between 1939 and 2005.

Table 1: Estimated characteristics of hydrologic response to the design storm observed on October 30th, 2004.

<table>
<thead>
<tr>
<th>Year</th>
<th>Excess precipitation mm (in)</th>
<th>Time to peak flow from onset of storm (h)</th>
<th>Peak discharge rate $m^3/s$ ($ft^3/s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1939</td>
<td>104.1 (4.1)</td>
<td>4.0</td>
<td>86 (3051)</td>
</tr>
<tr>
<td>1955</td>
<td>115.3 (4.5)</td>
<td>3.9</td>
<td>101 (3583)</td>
</tr>
<tr>
<td>1976</td>
<td>116.8 (4.6)</td>
<td>3.9</td>
<td>99 (3513)</td>
</tr>
<tr>
<td>2005</td>
<td>165.4 (6.5)</td>
<td>3.6</td>
<td>158 (5591)</td>
</tr>
<tr>
<td>2004a</td>
<td>n.a.</td>
<td>&lt;1h</td>
<td>166 (5870)</td>
</tr>
</tbody>
</table>

a. The time to peak and peak discharge rate are those reported for the Manoa Stream flood on the following web sites: http://hi.water.usgs.gov/projects/data_manoa_peaks.html and www.ph.noaa.gov/hnl/pages/events/ManoaFlood20041030/. Excess precipitation (rainfall that produces runoff and streamflow) estimates have not been made for this storm.
3.2 Animal-trapping results

Trapping demonstrated that rodent species that could be maintenance hosts of pathogenic *Leptospira* serovars were found in the watershed (Table 2). The species *Rattus rattus* (the black rat) predominated, and *Rattus norvegicus* (the brown rat), *Mus musculus* (domestic mouse), and *Herpestes auropunctatus* (the Indian mongoose) were also present. Table 3 includes serovars associated with these and other potential maintenance hosts that are found in the watershed. It is important to note that host specificity does not appear to be strict by either maintenance species or location [20, 39, 40]. However, rodent-sampling results from the Manoa watershed (see below) correspond with those presented Table 3. When trapping was extensive (1990, 1995) results demonstrated that infected hosts were present with an overall prevalence of 21/131 and that serovar icterohemorrhagia was detected in cultures from 13/21 rodents that tested positive for infection (Table 2).

4 Discussion

Flooding of the University of Hawaii, Manoa, campus was an unexpected event that transferred water, sediment and debris between distinct hydrologic units. When the campus was partially inundated, sediment and water contaminated with pathogenic *Leptospira* spirochetes infected workers involved in the clean-up. In the several weeks after the flood, two cases of leptospirosis in flood clean-up workers were confirmed by diagnostic testing. Also, 90 of 271 respondents to
Table 2: Results of rodent sampling in the Manoa Stream watershed, carried out by the Hawaiian Department of Health from 1990–2003. Columns report aggregated annual results of trapping by species (R: *Rattus rattus* (the black rat); N: *Rattus norvegicus* (the brown rat); H: *Herpestes auropunctatus* (mongoose), E: *Rattus exulans* (the Polynesian rat); M: *Mus musculus* (domestic mouse). Cells report number of individuals trapped per species, with number of positives reported as n/N (for example 8/107 individual *Rattus rattus* trapped were positive for leptospirosis in 1990). The number of infected individual species, with specific serovars, (I: icterohemmoragaie, B: ballum) is reported in the last column (for example, in 1990, cultures from kidneys of 4 *R. rattus* individuals were positive for serovar icterohemmoragaie, 4 were positive for serovar ballum, 1 *R. exulans* was positive for serovar ballum, and 1 *R. norvegicus* was positive for serovar icterohemmoragaie). When listed as mixed, several serovars were present.

<table>
<thead>
<tr>
<th>Year</th>
<th>R</th>
<th>N</th>
<th>H</th>
<th>E</th>
<th>M</th>
<th>Total species</th>
<th></th>
<th>Serovars observed, by species</th>
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<tbody>
<tr>
<td><strong>Intensive sampling efforts</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>1990</td>
<td>8/107</td>
<td>3/8</td>
<td>0</td>
<td>1/20</td>
<td>3</td>
<td>12/138</td>
<td></td>
<td>R: I(4), B(4)</td>
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<td>1/1</td>
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<td></td>
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<tr>
<td><strong>Total</strong></td>
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<td>21/231</td>
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<td>R: I(7), B(6)</td>
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<td>0</td>
<td>2</td>
<td>3/39</td>
<td></td>
<td>Mixed serovars</td>
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<td>1/4</td>
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<td>0</td>
<td>1/4</td>
<td></td>
<td>R: I(1), H: I(1)</td>
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<td>1</td>
<td>0</td>
<td>2/6</td>
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<td></td>
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<tr>
<td>2000</td>
<td>17</td>
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<td>6</td>
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<td>0</td>
<td>23</td>
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<td>R: I(1), H: I(1)</td>
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an e-mail survey limited to the University of Hawaii campus reported symptoms of leptospirosis [23]. Serovars that reacted in blood serum samples from the two confirmed cases showed elevated titres to several serogroups, including Australis, Autumnalis, Icterohaemorrhagiae, and Grippotyphosa [23].

Buildings affected by the flooding were constructed prior to 1980. This is significant because profound changes in land use in the Manoa watershed took place in the latter quarter of the 20th century. This suggests that although buildings were constructed in a swath that could be inundated by overflow waters from the Manoa watershed, flooding of this type had not been observed or anticipated at the time the buildings were constructed. The hydrologic analysis indicates that expected watershed response would have been significantly different when the buildings and Woodlawn bridge were sited and constructed, especially in terms of expected peak discharge quantities and flow energies. Prior to completion of the buildings and the bridge, even a storm with a low probability of occurrence may not have led to the type of flooding and overflow that occurred as a result of the intense storm of 2004. The Woodlawn bridge was especially critical because it had the potential to obstruct flow at a point that could cause overflow to the watershed containing the University of Hawaii. Although the amount of flow in the 2004 flood was less than the design capacity of the bridge, debris (including uprooted trees and accumulated sediment) reduced the capacity of the bridge, which led to flooding as high-velocity and -volume flows were forced out of the stream channel.

In order for pathogenic microbes to enter surface waters during flooding, at least four conditions must be met [16]:

1. a source of microbes must be present,
2. microbes must survive environmental stresses,
3. volumes of rainfall must be sufficient to generate drainage and
4. flows from areas that have a source of pathogens and the quantity of flow must have sufficient volume and energy to transport microbes to mainstream channels.

Each condition represents a series of micro- and macroprocesses about which little information is available for spirochetes, especially in the context of the living

Table 3: Observed associations between maintenance hosts and serovars of pathogenic leptospires.

<table>
<thead>
<tr>
<th>Animal host</th>
<th>Potentially associated serovars</th>
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<tr>
<td><em>Rattus</em> <em>spp.</em></td>
<td>Icterohaemorrhagiae** [24], ballum [41]</td>
</tr>
<tr>
<td><em>Mus musculus</em></td>
<td>Ballum [24], autumnalis** [46]</td>
</tr>
<tr>
<td><em>Sus scrofa</em></td>
<td>Australis**, pomona and grippotyphosa**, [47], Pomona [48]</td>
</tr>
<tr>
<td><em>Herpestes auroptatus</em></td>
<td>Autumnalis** [46]</td>
</tr>
<tr>
<td>Dogs</td>
<td>Grippotyphosa** [49]</td>
</tr>
</tbody>
</table>

**Patients had high titers for these serovars following the 2004 Manoa Flood.
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habits of rodent species. From the hydrologic analysis it appears that watershed development, especially addition of impervious surfaces, ensured that conditions 3 and 4 were met in the Manoa stream watershed. With regards to rodent populations, development created suitable habitat and food sources for rodent populations in the watershed, enhancing the likelihood that the first condition would be satisfied. In fact, research indicates that endemic infection rates are most related to commensal animal population density rather than environment [41]. The mode of transport of spirochetes in water has not been investigated (e.g. sorbed or not sorbed to sediment), nor is sufficient information available about condition 2 for spirochetes. However, several authors have speculated that wet environments are likely to favor survival of spirochetes and both vertical and horizontal transmission of disease within animal populations [37, 42].

Sporadic rodent trapping demonstrated that infected rodents were present in the watershed in five of the eleven years for which results are available prior to 2004. Several of the trapped rodents (Rattus rattus (the black rat), Rattus norvegicus (the brown rat), and Mus musculus (domestic mouse)) are closely associated with human presence. The results demonstrate that when sampling is intensive two species (R. rattus and R. norvegicus) were hosts of the same serovars found in patients with confirmed cases of leptospirosis following the 2004 flood. In addition, rodents infected with serovar icterohemmoraghia were found at several locations within 100 meters of the stream channel (Fig. 6). Although proximity is not the sole determinant of transport, runoff from almost all paved surfaces and roof tops in the watershed is conveyed directly to the mainstem of Manoa stream by gutters, culverts and concrete-lined channels. In addition, other potential maintenance hosts for pathogenic Leptospira were present in the watershed, but not tested. These include domestic dogs and feral pigs (Sus scrofa). Dogs may be regularly vaccinated as a prophylaxis against infection. However, the feral pig population potentially is a reservoir for leptospirosis. Feral pigs can be found throughout the upland portions of the watershed, though no studies have been conducted to determine numbers or rates of infection.

Research related to ecological factors associated with rat population dynamics suggests three characteristics likely to increase risk of waterborne disease occurrence, with respect to the four conditions listed earlier. First, both R. rattus and norvegicus have lifespans of 2–7 months, rarely exceeding a year [43, 44]. This suggests that sexually mature individuals will reproduce at least once in the course of a year, producing immunologically naïve newborns that will become reservoir hosts. Second, their range is limited, suggesting that short-term fluctuations in numbers due to reproduction and mortality will lead to very localized changes in density. Third, researchers have observed yearly density and reproductive cycles in populations of R. rattus, exulans and norvegicus [43, 44]. On the Hawaiian islands, these cycles correspond closely with annual cycles of precipitation, such that localized populations are likely to reach their maximum densities at the onset of the wet-weather months of October–May. This suggests that the source of pathogenic leptospires reaches a peak at approximately the same time that abstraction losses during rainstorms reach a minimum and transport potential is highest.
The Manoa watershed offers an illustration of the model presented in Fig. 1, though data to support a functional version of the model are lacking. The available data indicate that development led to a change in hydrologic response that may have facilitated transport of pathogens, resulting in an outbreak of leptospirosis caused by flooding. The enhanced hazard of flooding due to addition of impervious surface over the course of 65 years was likely accompanied by increased numbers of maintenance hosts of a microbial pathogen, which was important as an infectious agent during flooding in 2004. In this regard, the Manoa watershed may be a useful example for areas that are undergoing rapid expansion in previously undeveloped or lightly developed watersheds. As development progresses, populations of commensal animals, such as rodents, may increase significantly. This may be accompanied by proportional expansion of the types and amounts of microbial pathogens that may be transported by water. If addition of impervious surfaces significantly alters the hydrologic regime, increases in the magnitude of sources of pathogens may also increase the likelihood of zoonoses and horizontal transmission of disease to other populations, especially in downstream areas affected by flooding.

Significant anthropogenic change in watersheds can occur relatively quickly and have immediately noticeable effects. This is especially true in areas that are developing rapidly with influxes of industry and commerce, such as many of the
nations in Asia and the Asian subcontinent. In such areas, significant alterations of hydrologic regime may take place within a span of decades. This suggests that localized changes in hydrologic regime associated with development may be important to anticipate and manage, especially in areas where diseases that may be transmitted by water are endemic in host-animal populations.

Although flood control and infrastructure management and protection are critical elements of landscape planning during the early phases of development, the potential for synergism between emergence of endemic, waterborne zoonoses and flooding is unlikely to be emphasized. However, it is important to anticipate such links by characterizing maintenance host populations in advance of development (including cyclical trends in host population densities and prevalence of disease). When established, reservoir host-animal populations may be difficult to control without social and behavioral changes coupled with aggressive eradication programs [45]. If the potential for zoonosis associated with flooding is recognized prior to development, such information could be a critical component of planning that emphasizes downstream public-health protection.

Acknowledgements

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References


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