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A planetary health model for reducing exposure to faecal contamination in urban informal settlements: Baseline findings from Makassar, Indonesia

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ABSTRACT

Background: The intense interactions between people, animals and environmental systems in urban informal settlements compromise human and environmental health. Inadequate water and sanitation services, compounded by exposure to flooding and climate change risks, expose inhabitants to environmental contamination causing poor health and wellbeing and degrading ecosystems. However, the exact nature and full scope of risks and exposure pathways between human health and the environment in informal settlements are uncertain. Existing models are limited to microbiological linkages related to faecal-oral exposures at the individual level, and do not account for a broader range of human-environmental variables and interactions that affect population health and wellbeing.

Methods: We undertook a 12-month health and environmental assessment in 12 flood-prone informal settlements in Makassar, Indonesia. We obtained caregiver-reported health data, anthropometric measurements, stool and blood samples from children < 5 years, and health and wellbeing data for children 5–14 years and adult respondents. We collected environmental data including temperature, mosquito and rat species abundance, and water and sediment samples. Demographic, built environment and household asset data were also collected. We combined our data with existing literature to generate a novel planetary health model of health and environment in informal settlements.

Results: Across the 12 settlements, 593 households and 2764 participants were enrolled. Two-thirds (64·1%) of all houses (26·3–82·7% per settlement) had formal land tenure documentation. Cough, fever and diarrhoea in the week prior to the survey were reported among an average of 34.3%, 26.9% and 9.7% of children aged < 5 years, respectively; although proportions varied over time, prevalence among these youngest children was consistently higher than among children 5–14 years or adult respondents. Among children < 5 years, 44·3% experienced stunting, 41·1% underweight, 12.4% wasting, and 26.5% were anaemic. There was self- or carer-reported poor mental health among 16.6% of children aged 5–14 years and 13.9% of adult respondents. Rates of potential risky exposures from swimming in waterways, eating uncooked produce, and eating soil or dirt were high, as were exposures to flooding and livestock. Just over one third of households (35.3%) had access to municipal water, and contamination of well water with *E. coli* and nitrogen species was common. Most (79·5%) houses had an in-house toilet, but no houses were connected to a piped sewer network or safe, properly constructed septic tank. Median monthly settlement outdoor temperatures ranged from 26·2 °C to 29.3 °C, and were on average, 1·1 °C warmer inside houses than outside. Mosquito density varied over time, with *Culex quinquefasciatus* accounting for 94·7% of species. Framed by a planetary health lens, our model includes four thematic domains: (1) the physical/built environment; (2) the ecological environment; (3) human health; and (4) socio-economic wellbeing, and is structured at individual, household, settlement, and city/beyond spatial scales.

Conclusions: Our planetary health model includes key risk factors and faecal-oral exposure pathways but extends beyond conventional microbiological faecal-oral enteropathogen exposure pathways to comprehensively account for a wider range of variables affecting health in urban informal settlements. It includes broader ecological interconnections and planetary health-related variables at the household, settlement and city levels. It proposes a composite framework of markers to assess water and sanitation challenges and flood risks in urban informal settlements for optimal design and monitoring of interventions.

1. Introduction

Urban informal settlements, home to one billion people, pose a significant planetary health challenge. (UN-Habitat, 2020) Planetary health, "the health of human civilisation and the state of the natural systems on which it depends", recognises the emerging chronic and acute threats to natural and human-made systems, which are essential to humanity's survival, from unsustainable and inequitable processes. (Whitmee et al., 2015) Planetary health considers health comprehensively (mental, social, and physical) and links human health with environmental health through a whole-of-systems framing, recognising that urban population health is intimately tied to urban socio-ecological systems.

Informal settlements intersect with planetary health in several ways. Their vulnerability to flooding and climate change risks such as rising sea levels and more extreme weather events exacerbates existing health inequities such as the contamination of waterways and ecosystems, urban heat islands, and prevalence of disease vectors. (Satterthwaite et al., 2020) High inhabitation densities and precarious housing lead to intense interactions between humans, animals and environmental systems. Due to their unplanned and unregulated nature and morphological growth, informal settlements also contribute to the degradation of habitats and natural ecosystems. (Corburn and Sverdlik, 2017) Public health pandemics, such as COVID-19, exacerbate the challenges in already highly vulnerable urban informal settlements. (French et al., 2020) The convergence of these human-environment factors has detrimental effects on population health and wellbeing, with impacts on mortality, morbidity, mental health, and child development. (Lilford et al., 2017; Clasen et al., 2015)

Importantly, inadequate sanitation in informal settlements is a leading cause of environmental contamination and directly compromises population health and wellbeing. (Corburn et al., 2019; Satterthwaite et al., 2019) Inadequate sanitation services and polluted water supplies are known to be leading drivers of diarrhoeal disease, and globally, diarrhoea represents the second highest cause of mortality among children under the age of five accounting for approximately 500,000 deaths in 2015. (Liu et al., 2016)

Water, sanitation and hygiene (WASH) interventions can reduce risk factors associated with diarrhoeal disease in resource-constrained settings. (Wolf et al., 2018; Dey et al., 2019) Traditional WASH models have generally focused on drinking water availability, source and quality; availability and usage of toilets; handwashing hardware and behaviours; and specific health outcomes such as carer-reported illness (particularly diarrhoea), child growth and nutritional markers. Recent trial findings, however, have called into question the effect size of such interventions, (Cumming et al., 2019) leading to calls for 'transformative WASH' approaches that are 'radically more effective' in reducing faecal contamination in the environment and that more comprehensively address the socio-cultural, economic, environmental and ecological contexts that determine intervention effectiveness and sustainability. (Levy and Eisenberg, 2019) Implementation of broader interventions necessitate

monitoring of an expanded range of outcomes, requiring the development of new models upon which to design and monitor comprehensive water and sanitation interventions in urban informal settlements.

In this paper, drawing on baseline findings from the Revitalising Informal Settlements and their Environments (RISE) transdisciplinary research program, we bring together 'transformative WASH' and planetary health in order to generate an empirically grounded conceptual model of health and environment in urban informal settlements. Our starting point is the core WASH theory of change: reducing child exposure to faecal-oral contamination will improve gastrointestinal health and thus physical development outcomes. While our focus is on faecal-oral exposure pathways, we aim to extend this to a whole-of-systems analytical approach examining broader contextual pathways that impact on population health, including built environment factors, environmental conditions, disease vectors, and wellbeing variables. We hypothesise that this more complete assessment of the causal pathways and interlinkages beyond existing models and narrow sets of health indicators provides a framework for measuring the effectiveness of water and sanitation interventions.

2. Methods

2.1. Study design

The RISE program is implementing a randomised controlled trial (RCT) involving delivery of 'water-sensitive' infrastructure to 24 informal settlements (12 in Suva, Fiji, and 12 in Makassar, South Sulawesi, Indonesia). (Brown et al., 2018) The intervention aims to reduce exposure to contaminated environments by improving community water and sanitation services. (Leder et al., 2021) The data presented in this paper was collected as the baseline (pre-intervention) Makassar dataset for the RCT (see: Supplementary Material for further information). This baseline study followed a repeated cross-sectional design over a period of a 12-months in order to capture seasonal changes.

2.2. Study location

The study sites include 12 geographically discrete, flood-prone informal settlements located in Makassar, South Sulawesi, Indonesia's sixth largest city with a population of 1·5 million. (BPS Makassar Municipality, 2020) Informal settlements account for almost one-third (30%) of Indonesia's urban population. (United Nations. SDG monitoring dataset [Internet]., 2020) Approximately 80% of the urban population in Indonesia has access to basic sanitation and 95% has access to basic drinking water, while the rate of access to 'safely managed' water and sanitation services is reported as 0%. (UNICEF, 2019)

2.3. Site selection and participant recruitment

The 12 settlements were purposively selected with governmental cooperation based on eligibility criteria established for the randomised controlled trial. (Leder et al., 2021) The 12 settlements were selected from a shortlist of more than 100 based on the following criteria: (a) residents representative of the most vulnerable populations; (b) poor water and sanitation services; (c) poor drainage and/or flooding conditions; (d) high risk of water-borne and -related diseases; (e) size (consisting of approximately 30–100 houses); (f) at least 5 children < 5 years of age (balancing sample size and cost / logistical issues); (g) secure land tenure; (h) no other ongoing or planned interventions; and (i) physically separated from other settlements with clear physical boundaries (not contiguous with neighbouring areas). Approximately 20 settlements were initially considered as potentially appropriate, and were ranked according to their match to the above criteria and geographic spread across Makassar. The 12 settlements chosen were considered most suitable for inclusion; they are in 5 city districts and all successfully gained community support. A structured, six-month community engagement process was implemented to obtain the informed consent of study participants. All households and all residents living within the settlement boundaries were invited to participate in the trial. Adults eligible for participation were identified as: over 18 years of age, married or having children. Community level consent was secured in May 2018 through the 12 Community Engagement Councils that had been formed to represent each site. Individual participant enrolment and consent took place in July–August 2018.

2.4. Data collection

Data collection took place between October 2018 and September 2019 (Table 1). All surveys were standardised and administered on hand-held tablets. The initial survey undertaken with each household collected data on household composition, environmental risks, housing quality, water and sanitation services, solid/hard waste practices, and household assets. This survey was preferentially directed to the adult female head of household.

Child and adolescent health was measured through a standardised caregiver-reported quantitative survey, preferentially answered by the adult caregiver who had spent time with the child on most days in the past week. (Leder et al., 2021) This survey captured health practices, symptoms (including diarrhoea) and exposures to enteropathogens. Survey questions about children < 5 years of age were administered four times at three-month intervals and about children 5–14 years (maximum of two per household) were administered twice at six-month intervals (Table 1). In March 2019, trained anthropometrists measured length or height and weight of all children < 5 years of age to generate length/height-for-age (LAZ/HAZ), weight-for-age (WAZ), and weight-for-length/height (WLZ/WHZ) Z-scores, calculated using R library ki-tools/growthstandards, R version 4.0.2. Based on the WHO recommendations, (de Onis et al., 2004) anthropometry measurements that were biologically implausible were excluded from Z-score analyses. Stunting, wasting and underweight were defined based on WHO criteria. (Black et al., 2013) During the same visit, phlebotomists measured haemoglobin concentrations in venipuncture whole blood samples at the point of collection using a portable spectrophotometer (Hemocue 301). Anaemia was defined as < 110 g/L. (WHO, 2020) Faecal samples were collected on a quarterly basis for future examination of enteropathogens, microbial communities, and antimicrobial resistance markers.

Human wellbeing was measured twice at six-month intervals through a standardised quantitative survey involving all households, preferentially administered to (i) primary caregivers where households contained children under 15 years, and (ii) female head or (iii) other adult for households with no children. The survey focused on psychological, social and economic outcomes, including validated measures of subjective wellbeing, depression (CES-D-10), quality of life (PedsQL), time-use, major events, social cohesion, and household assets. Evaluative wellbeing measurements (levels of satisfaction) in different life domains were collected from adult respondents twice at six-month intervals using a 0–10 scale. Emotional functioning of children was assessed using the Parent Report Paediatric Quality of Life Inventory™ 4.0 Generic Core Scales (PedsQL) five emotional functioning dimension items. Each item asks how often the child experienced certain emotions over the past month with possible responses ranging from 0 = 'Never' to 4 = 'Almost Always'. Item scores are transformed across a range from 0 to 100 (such that 0 = 100, 1 = 75, 2 = 50, 3 = 25, 4 = 0). The emotional functioning score is the mean of item scores, where a higher score reflects higher emotional functioning. The CES-D-10 score is calculated by summing answers (some reverse coded) to the 10 questions, which range from 0 (rarely or none of the time) to 3 (all of the time). Respondents were asked to rate each life satisfaction domain on a scale from 0 = 'Completely Dissatisfied' to 10 = 'Completely Satisfied'.

Environmental monitoring included chemical analyses of water, microbiological analyses of water and soil/sediment, surveys of vector species and abundance (mosquitoes and small mammals), and hourly indoor and outdoor temperature measurements using shaded iButtons (DS1921G/DS1923-F5#). Water (environmental water, river/creek, seawater, well, deep well, municipal or rainwater tank) and soil/sediment samples were collected from consistent locations quarterly. Environmental water is defined, for this study, as greywater and stormwater occurring within communities that could not be directly associated with larger natural water bodies (river/creeks/estuaries/seawater). Soils and sediment samples were taken from areas of "high exposure risk" of primary contact events based on initial site surveys (e.g. children's play areas and primary access pathways). Fresh animal faeces samples, obtained from local agricultural (foodstock), domestic or feral animal species, were also collected, *ad hoc*, from each community during sampling periods.

In total, 226 water samples (Table S8) were collected across four sampling campaigns (113 shallow well, 44 deep/bore well, 20 municipal, 1 rainwater tank, 34 environmental water, 14 river/creek/seawater) and tested for *Escherchia coli*, ammonia, nitrate and nitrite. Comparison was conducted on samples collected based on attributed source (n = 181). Data collected in October 2018 was omitted to enable statistical evaluation based on a single quantification method; October 2018 water samples were quantified using the IDEXX Colilert method (IDEXX, USA) as per manufactures instructions. All remaining campaigns were quantified using TECTAlert-CCA method on the Tecta B16 system (TECTA, Canada) as described by the manufacturer and as such are reported as cfu/100 mL. For analysis, sea water samples from the remaining 3 campaigns (n = 4) were included in the river/creek classification. Rainwater (n = 1) was excluded from analysis.

BG sentinel II traps (~15 per settlement) were used inside or outside houses to capture mosquitoes over a three-day period each quarter. Mosquitoes were identified using morphological keys, and the sex, species, and counts were recorded. (Rueda, 2004; Reuben et al., 1994) Outdoor trap-based surveys for rodents and other small mammals (e.g. shrews) were conducted quarterly, over a 6-week period, using standard lethal traps and complementary non-lethal ink tracking methods. Traps were set for 3–4 nights per site per quarter using a grid-based design within sites to equate trapping effort across sites of very different size.

2.5. Data and sample analysis

In general, results are presented as population percentages or means, along with range of settlement percentages or means (minimum, maximum), unless otherwise stated. Where repeated observations are available, data is presented by sampling campaign. All human and environmental samples were processed and analysed in the RISE laboratory at Hasanuddin University, Makassar, with the exception of water chemistry analyses which were undertaken in a local water testing laboratory. Details of laboratory analyses and procedures have been described previously. (Leder et al., 2021) Seasonality effects, based on longitudinal comparison of *E. coli* concentrations within soil and water environments, were estimated via the Spearman rank correlation coefficient, using GraphPad Prism v7 software package. Comparison of

Table 1
Methods and survey and sampling collection timeline.

Item		Information	Inaugural /Baseline (T0)	Quarter 1 (T1)	Quarter 2 (T2)	Quarter 3 (T3)
Demographics	Household	Head of household; Number of members, number living in the household	Nov/Dec 2018	-	-	Sep 2019
	Individual residents' characteristics	Name, date of birth, sex, marital status, relationship to head of household, education level, literacy	Nov/Dec 2018	-	-	-
Built environment	Housing quality	Floor, wall, and roof materials; number of rooms	Nov/Dec 2018	-	-	-
	Tenure	Land ownership/tenure, occupation tenure	Nov/Dec 2018	-	-	-
	Water services	Water sources, access, treatment methods, and cost	Nov/Dec 2018	-	-	-
	Sanitation services	Sanitation access, type, ownership, and disposal; garbage disposal	Nov/Dec 2018	-	-	-
	Environment	Local flooding events; child environmental exposures	Nov/Dec 2018	Feb/Mar 2019	Jun 2019	Sep 2019
Human health and wellbeing	Health survey – child <5 years	Symptoms, healthcare utilisation	Nov/Dec 2018	Feb/Mar 2019	Jun 2019	Sep 2019
	Health survey – child 5-14 years	Symptoms, healthcare utilisation, mental health	Nov/Dec 2018	-	Jun 2019	-
	Health survey – (targeted caregiver / female household head)	Symptoms, healthcare utilisation, mental health	Nov/Dec 2018		Jun 2019	
	Anthropometrics	Height and weight for children <5 years		Feb/Mar 2019	-	-
	Blood	Haemoglobin for children <5 years		Feb/Mar 2019	-	-
	Stool	Soil transmitted helminths		Feb/Mar 2019	Jun 2019	Sep 2019
	Socio-economic survey	Individual primary activities and time use, household assets, self-assessed socioeconomic status and life satisfaction	Nov/Dec 2018	-	Jun 2019	-
Water, environment and vectors	Water (environmental, well, municipal)	*E. coli*, nitrogen, pH, temperature, turbidity, conductivity, dissolved oxygen	Oct 2018	Feb 2019	May 2019	Aug 2019
	Sediment/soil	*E. coli*	Oct 2018	Feb 2019	May 2019	Aug 2019
	Animal faeces	Local agricultural (foodstock), domestic or feral animals	Oct 2018	Feb 2019	May 2019	Aug 2019
	Thermal environment	Temperature and humidity	Deployed Oct 2018; continuous monitoring (1-2 hourly); Quarterly data upload.			
	Mosquitoes	Mosquito species and relative abundance	Oct 2018	Jan 2019	Apr 2019	Jul 2019
	Rodents*	Small mammalian pest species and relative abundance	Apr/May 2019	Jul/Aug 2019	Oct/Nov 2019	Jan/Feb 2020

*The 'baseline' rodent sampling extended beyond the 12-month baseline (Oct 2018- Sep 2019) due to field logistics and longer start-up times.

water samples collected between February and August 2019 (n = 171) was conducted using the Kruskal-Wallis test.

2.6. Ethics

Ethics review and approval was secured by the Monash University Human Research Ethics Committee (Melbourne, Australia; protocol 9396), Monash University Animal Ethics Committee (protocol ID16351) and the Ministry of Research, Technology and Higher Education Ethics Committee of Medical Research at Universitas Hasanuddin (Makassar, South Sulawesi, Indonesia; protocols UH18020110 and UH18080446). The RISE trial is registered on the Australian New Zealand Clinical Trials Registry (ANZCTR) (Trial ID: ACTRN12618000633280). All study settlements, households, and caregivers/respondents provided informed consent.

3. Results

3.1. Demographic and built environment characteristics

The 12 settlements varied in size, with an area of 2,846–27,635 m^2 (median: 9,584 m^2) per settlement and 18–113 (median: 39) households per settlement. Households had 1–13 occupants with an average household occupancy per settlement of 4·07–4·98 (median: 4·67; Fig. 1). A total of 2,764 people (1,355 female, 1,409 male) across 593 households (Table S15), in 570 houses were enrolled, representing greater than 95% of all potentially eligible households. The median age of all household members was 24·9 years (0·0–93·0 years) and 10.2% were < 5 years of age. Across the study settlements, the proportion of household respondents having lived in their settlement for greater than 10 years (including "whole life") varied from 50·0% to 94·8% (Table S15).

The majority of houses had some masonry walls (42·1–86·1% across settlements), with corrugated iron/tin and wood also used. On average, each house had 5.6 rooms (settlement average 4·4–6·9 rooms per house; Table S2). Two-thirds (64·1%) of all houses (26·3–82·7% per settlement) had formal land tenure documentation (either a freehold ownership title or sale and purchase deed). Most households (82·6%) were 'owner-occupier' (65·8–95·5% per settlement; Table S2).

Compared with households in urban areas of South Sulawesi and households in all Indonesian urban areas, (National Population and Family Planning Board – BKKBN, 2017) households across the participating settlements had comparatively low ownership rates of air conditioners (4·4% vs 22·8%), car/truck/vans (5·6% vs 23·3%), computers (18·2% vs 39·1%), washing machines (38·6% vs 46·7%), and bank accounts (45·0% vs 66·8%), whereas ownership rates of bicycles, refrigerators, motorcycles, electric fans, and mobile phones were similar to non-study urban households in the Province (Table S16).

3.2. Human health and wellbeing

Health symptom responses were available from an average of 269 children < 5 years (41% female), 373 children ages 5–14 years (48% female), and 546 adult respondents (88% female) per survey round (Table 2). Results reported here are aggregate results across the study population. Participation rates were 83–85% among targeted households for the three post-baseline surveys.

A persistent cough in the prior 7 days was the most common symptom reported in each age group with a prevalence of 34·3% of children < 5 years of age, 13·6% of children 5–14 years of age and 18·5% of adult respondents. In general, children < 5 years of age had a higher prevalence of cough, fever, and diarrhoea compared to older children (5–14 years of age) and adult respondents (Table 2).

According to caregivers, 20% of children < 5 and 16% of children 5–14 years were in very bad, bad, or moderate health while 31% of adult respondents reported very bad, bad, or moderate health (rather than good or very good health; Table 2). The mean (±sd) LAZ/HAZ was –1·81 ± 1·18, WAZ was –1·71 ± 1·02, and WLZ/WHZ was –0·97 ± 1·02, with 44·3% of children experiencing stunting, 41·1% underweight, and 12.4% wasting (Table S13). The mean haemoglobin concentration was 115·1 g/L (48·0–153·0), with 26·5% prevalence of anaemia, including 2·1% severe (Table S13).

The average 7-day diarrhoea prevalence was 9·7% for children < 5 years, 2·7% for children 5–14 years, and 4·9% for adult respondents (Table 2). Across all age groups, reported rates of diarrhoea were higher in the wet season (November-January) than the dry season (June-August). For example, 14·5% of children < 5 years had diarrhoea in the wet season assessment compared with 7·2% in the dry season. Multimorbidity was commonly seen, especially among children < 5 years, among whom (for example), across the four time periods an average of 27·0% had one of diarrhoea, cough or fever reported in the last 7 days, 17·1% had two of these symptoms, and 3·2% had all three symptoms reported. For children aged 5–14 years, the corresponding figures were 16·6%, 5·0% and 0·5%, respectively, and for adults 19·1%, 5·8% and 0·6%. In the prior 3 months, 35·1% of children < 5 years, 19·3% of children 5–14, and 27·1% of adult respondents had an outpatient healthcare visit because they were sick or injured. Notably, there were high rates of reported antibiotic use with 42·5% of children < 5 years given antibiotics after an outpatient visit (Table 2).

Sources of child environmental exposures investigated included swimming or playing in local waterways, eating uncooked produce and eating dirt or soil. The highest proportion of children swimming or playing in local waterways was reported in February/March 2019, with 85·2% (55·6–100·0%) of children < 5 years of age reporting this activity (Table S12). The proportion of children eating uncooked produce was relatively consistent over time (~80% of children < 15 years), although there was some variation between settlements (55·6-100·0%). Most children < 5 years (84·2%) were reported as eating soil or dirt, with variation across the settlements (55·6-100·0%).

Caregivers reported that 15·5% of children 5–14 years had poor mental health, while 13·9% of adult respondents had poor mental health (Table 2). Mean overall life satisfaction was lower than mean scores in OECD countries (6·9 vs 7·4). (Graafland and Lous, 2018) Satisfaction levels of adult respondents were lowest for financial situation, quality of housing, and state of the settlement. They were most satisfied with how they expect to feel in five years' time, feeling part of their community, their safety, and the amount of free time they have (Table S18).

3.3. Water, sanitation and the environment

Most of the settlements are on flat, low-lying topography with limited or no formal drainage to effectively and safely drain storm water, which causes prolonged ponding/flooding after rainfall. Houses were particularly affected by flooding in February/March 2019, the end of the wet season; overall 49·4% of households reported flooding outside or under their house within the 3 months to March (10·0%–100·0% by settlement), and 30·6% reported flooding with water entering the house over the same period (0·0%–100·0% by settlement; Fig. 2).

Household water sources, quality, and use are complex. Over two thirds (68·2%) of households reported using bottled water (which includes local refill from the drinking water depot; 20·0%–100·0% by settlement) as a primary drinking water source and 19·8% reported municipal water (reticulated supply; 0·0%–80·0%); other primary water sources included bore well, shallow well, rainwater, tanker and cart water (Table S5). Water sources for non-drinking purposes were also diverse with households using bore water, shallow well, mains, rain water, bottled, tanker and cart for household activities (personal hygiene, laundry, washing dishes, cleaning, or agricultural purposes; Table S5).

Apart from municipal water (and bottled water which was untested), water quality across all sources was generally poor. Contamination of deep well and well water did not meet WHO drinking water guidelines (WHO, 2017) for *E. coli* and nitrogen chemical species (Fig. 3). Municipal water *E. coli* measurements were consistently below

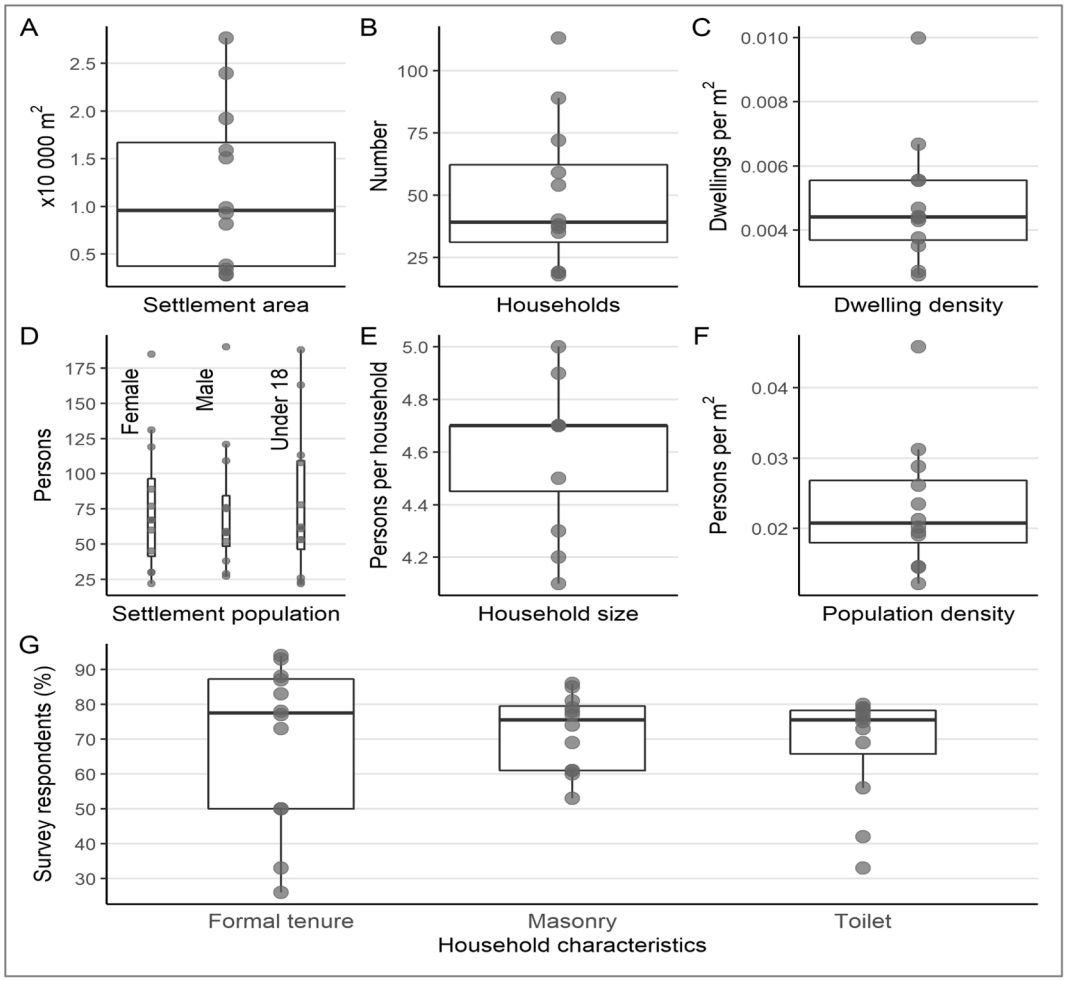

Fig. 1. Summary of settlement characteristics: a) settlement area, b) number of households per settlement, c) dwelling density of settlements, d) settlement population demographics, e) household size, f) settlements population density, g) percentage of households with formal tenure, houses with some masonry walls and having an indoor toilet. Solid circles represent settlement-level values.

detection across all three sampling campaigns, meeting WHO guidelines (no detection of *E. coli*) and Indonesian standards (Indonesian Ministry of Health Regulation, 2017). Municipal water also had low concentrations of nitrate (<5·02 mg/L), nitrite (<0·18 mg/L) and ammonia (<0·33 mg/L; Fig. 3). Of those with access to municipal water (35·3% of houses), 80·6% reported that it was "available everyday through the whole year" (Table S6).

Levels of *E. coli* within environmental water were at concentrations considered by the WHO as indicative of raw sewage contamination (Fig. 3, S1 and S2). Similarly, measured *E. coli* concentrations in river water samples were on average 3 log units higher than the recommended WHO guidelines for 'good-quality' inland water sources (USEPA, 2012) (2·6 $\log_{10}$ cfu/100 mL vs 5·4 $\log_{10}$ cfu/100 mL), indicative of significant faecal pollution.

Soil and sediment samples from the local environment showed *E. coli* contamination across all four campaigns. Measured *E. coli* concentrations ranged from a mean of $1x10^2$ in October 2018 to $1x10^4$ MPN/g (dry weight) in February 2019 (Figure S2), although there was no distinct seasonal variation.

Rates of open defecation were comparable to the national urban average (3·8%) (WHO and UNICEF, 2019) with 5·3% of respondents reporting that adults defecate outdoors (0·0–18·4% by settlement) and 8·2% reporting that children defecate outdoors (in houses with children, 0·0–17·9% by settlement; Table S3). Most (79·5%) houses had an in-house toilet (50·0–94·1% by settlement; Fig. 1 and Table S2), and 18·1% of houses shared their toilet with one or more other houses (4·8–50·0% by settlement). None of the houses were connected to a piped sewer network or safe, properly constructed septic tank (i.e. no toilets were connected to 'safely managed sanitation' as defined in Sustainable Development Goal target 6.2), although 65·3% of houses reported that human waste was discharged to a septic system with no base (42·1–86·3% by settlement; Table S3).

The median monthly settlement outdoor temperature ranged from 26·2 °C in December 2018 to 29.3 °C in October 2019, and was, on average, 1·1 °C warmer inside houses than outside (Figure S4). The highest monthly maximum temperature (95% quantile of all data points) recorded was 35·6 °C in October 2019 and the lowest minimum temperature (5% quantile of all data points) was 21·7 °C in August 2019. The air temperature in and around settlement houses was predominantly within the temperature range recorded by the local weather station, but minimum temperatures across settlements were several degrees warmer than temperatures recorded by the weather station and contributed to periods of prolonged heat. (Ramsay et al.)

3.4. Animals

A total of 44,012 mosquitoes was captured and identified predominantly as *Culex quinquefasciatus* (94·7%) and *Aedes aegypti* (4.9%). Small numbers of other species were caught including *Anopheles* species, *Aedes albopictus*, *Culex sitiens*, a *Uranotaenia* species, and a *Mansonia* species. Counts across campaigns suggest seasonal variation, and female mosquitoes, responsible for the transmission of disease, were captured in higher numbers than males (Table S10, Figure S6).

Table 2
Carer- or self-reported health outcomes.

Date	Response demographics			Health indicators									Health self-assessment	
	n	% female	Median age, years	Visited doctor in prior 3 months (%)	Given antibiotics after doctor's visit (%)	Fever in the past week (%)	Cough in the past week (%)	Difficulty breathing in the past week (%)	Diarrhoea in the past week (%)	Skin infection in the past week (%)	Injury in the past week (%)	Toothache in the past week (%)	Poor general health *(%)	Poor mental health** (%)
Children under 5 years of age														
T0 Nov/Dec 2018	282	46.5 (30.0, 63.6)	2.6 (2.1, 3.2)	29.8 (12.5, 40.0)	39.3 (42.9% don't know) (12.5, 100.0)	29.4 (12.5, 41.0)	29.4 (0.0, 40.9)	1.4 (0.0, 4.5)	14.5 (0.0, 30.0)	12.8 (0.0, 29.4)	5.0 (0.0, 25.0)	6.4 (0.0, 30.0)	29.1 (0.0, 90.0)	N/A
T1 Feb/Mar 2019	282	31.2 (13.6, 66.7)	2.6 (1.9, 3.1)	42.9 (16.7, 63.6)	57.0 (26.4% don't know) (33.3, 100.0)	31.9 (10.5, 55.6)	45.4 (27.3, 83.3)	5.0 (0.0, 22.2)	8.9 (0.0, 33.3)	16.0 (0.0, 28.2)	3.5 (0.0, 6.1)	6.0 (0.0, 11.1)	N/A	N/A
T2 Jun 2019	250	41.6 (25.0, 60.0)	2.8 (2.3, 3.2)	32.4 (6.1, 63.2)	43.2 (33.3% don't know) (0.0, 100.0)	24.0 (11.1, 39.6)	32.0 (10.0, 50.0)	2.4 (0.0, 15.8)	7.2 (0.0, 25.0)	5.6 (0.0, 16.7)	3.6 (0.0, 10.0)	6.0 (0.0, 20.0)	18.0 (0.0, 50.0)	N/A
T3 Sep 2019	261	42.9 (26.1, 71.4)	2.8 (2.1, 3.3)	35.2 (14.3, 50.0)	30.4 (20.6% don't know) (0.0, 100.0)	22.2 (5.0, 45.5)	30.3 (0.0, 72.3)	1.9 (0.0, 6.3)	8.0 (0.0, 14.3)	6.9 (0.0, 42.9)	1.9 (0.0, 10.0)	3.1 (0.0, 20.0)	11.9 (0.0, 60.0)	N/A
Average	269	40.6	2.7	35.1	42.5	26.9	34.3	2.7	9.7	10.3	3.5	5.4	19.7	
Children 5–14 years of age														
T0 Nov/Dec 2018	402	47.3 (33.3, 71.4)	9.3 (7.4, 11.7)	18.7 (10.0, 32.1)	n/a	15.0 (0.0, 50.0)	11.7 (0.0, 26.7)	2.7 (0.0, 6.8)	3.0 (0.0, 8.7)	9.0 (0.0, 33.3)	3.5 (0.0, 14.3)	11.0 (0.0, 24.2)	18.0 (4.3, 50.0	15.0 (2.2, 42.9)
T2 Jun 2019	343	48.4 (33.3, 71.4)	9.5 (7.9, 12.3)	19.8 (0.0, 35.7)	n/a	9.0 (0.0, 18.4)	15.5 (4.8, 30.0)	1.7 (0.0, 12.5)	2.3 (0.0, 8.7)	5.8 (0.0, 26.9)	4.1 (0.0, 15.4)	5.2 (0.0, 28.6)	14.0 (0.0, 33.3)	13.4 (0.0, 23.1)
Average	373	47.9	9.4	19.3		12.0	13.6	2.2	2.7	7.4	3.8	8.1	16.0	14.4
Adult Respondents														
T0 Nov/Dec 2018	593	89.7 (80.5, 98.3)	39.6 (36.8, 47.9)	25.3 (10.5, 32.4)	n/a	11.1 (4.2,21.1)	16.2 (6.9, 26.3)	6.9 (2.2, 14.3)	6.4 (0.0, 11.1)	13.3 (7.5, 21.1)	2.5 (0.0, 10.5)	10.3 (0.0, 22.9)	37.9 (19.1, 78.9)	12.8 (5.6, 21.1)
T2 Jun 2019	498	87.1 (75.0, 95.5)	39.9 (36.2, 49.5)	28.9 (22.2, 47.1)	n/a	7.4 (0.0, 18.8)	20.7 (13.6, 40.0)	6.0 (0.0, 16.0)	3.4 (0.0, 12.5)	6.6 (0.0, 21.4)	0.4 (0.0, 3.7)	5.8 (0.0, 12.3)	24.3 (16.0, 37.5)	N/A
Average	546	88.4	39.8	27.1		9.3	18.5	6.5	4.9	10.0	1.5	8.1	31.1	12.8

*General health reported as very bad, bad or moderate (rather than good or very good).
**Poor mental health for children 5–14 years was calculated from PedsQL emotional functioning score < 70; $n = 401$ responses at T0, $n = 343$ at T2; poor mental health for adults was calculated from CES-D-10 scores ≥ 10.
The minimum and maximum percentages across the 12 settlements are shown in brackets.

Small mammal trapping found variation in the relative abundance of species across both seasons and sites (Figure S7). Over four quarterly surveys, 314 small mammals were trapped, of which 74·8% were Asian house shrews (*Suncus murinus*). The remainder were primarily brown rats (*Rattus norvegicus*; 22·9%), though a few Pacific rats (*R. exulans*), rice-field rats (*R. argentiventer*), and incompletely identified individuals (*Rattus* sp.) were also captured. All species trapped are capable of spreading disease to humans. Both rats and shrews had their highest observed median relative abundance around the wet season, but the peak for rats occurred earlier (January, closer to the height of the wet season) than the peak for shrews (April).

Animals, including livestock, were common within all 12 settlements, with households reporting the following animals in their local environment (settlement means reported as inside the house; immediately outside of their house): cats (79·3%; 97·9%), geckos (89·4%; 90·7%), mice/rats (80·4%; 95·3%), chickens and ducks (31·2%; 97·2%), dogs (1·1%; 42·1%), domesticated birds (2·4%; 13·4%), and livestock (0·0%; 31·6%) (Table S11).

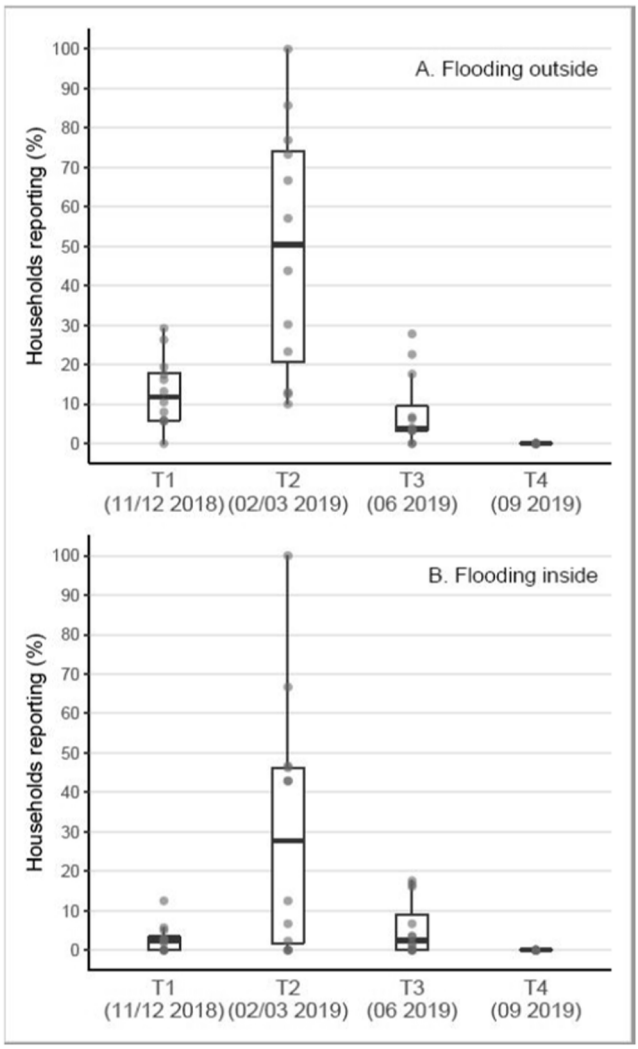

Fig. 2. Flooding occurrence (past 3 months) outside and inside houses by season (% of houses/ households). Solid circles represent settlement percentages. Note: Flooding inside asked of houses that reported flooding outside their house. T0 asked of 570 houses, T1 asked of 223 houses, T2 asked of 501 households, T3 asked of 214 households.

4. Discussion

In this study, we present survey and sampling data collected from 12 informal settlements in Makassar, Indonesia, over a 12-month period. Increasing global recognition of the multifactorial and interdependent social, demographic and environmental factors that directly and indirectly influence health, including gastrointestinal health of young children, requires increasingly complex data monitoring and analyses in

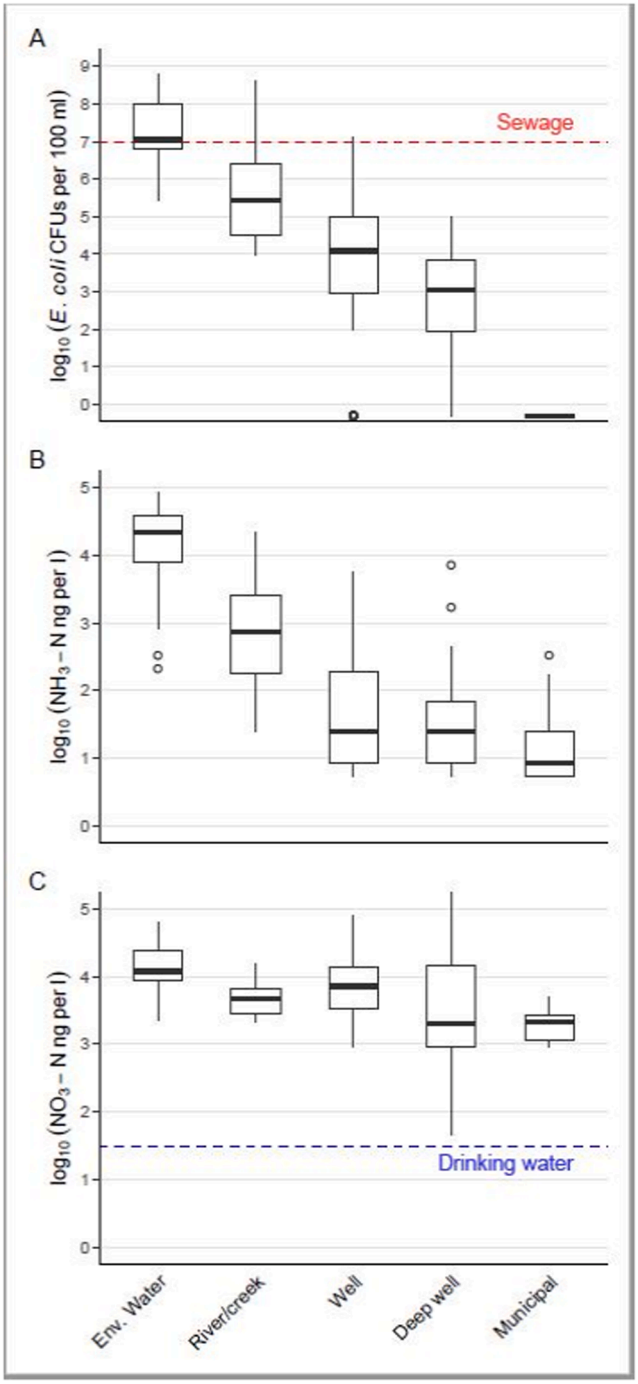

Fig. 3. Water quality across all water sample types for A) E. coli, B) ammonia, and C) nitrate. Within Figure A the dotted line labelled "Sewage" represents average E. coli concentrations in raw sewage as reported by WHO (WHO, 2003). Acceptable nitrate concentration, as defined by the WHO Drinking Water Guidelines (WHO, 2017), is identified in Figure C. No health-based guidelines currently exist for ammonia. Open circles represent outliers.

order to capture significant factors driving morbidity and optimal priorities for interventions to achieve health improvements. (Sima et al., 2013) Our multidisciplinary dataset provides a broad picture of environmental and health conditions among the included informal settlement populations.

We have deliberately targeted vulnerable informal settlement communities, prone to flooding and water insecurities, and lacking in safely managed sanitation, in order to maximise benefits from our future delivery of a water-sensitive intervention. The survey and microbiological findings suggestive of highly contaminated water and soil (as evidenced by *E. coli* concentrations) confirm that the settlements studied here are indeed prone to the environmental contamination problems typical of informal settlements generally. The frequency of outdoor flooding events which redistribute contamination across the flat, low-lying topography within settlements, combined with limited safe access (streets/roads) to houses, internal flooding of houses during peak events, high levels of animals, and frequency of children playing in the contaminated waters, collectively result in high-risk exposure pathways.

The mean reported rates of diarrhoea, fever and respiratory illness among children under 5 in the week prior to the survey (9·7%, 25·9% and 34·3%, respectively) are a consequence of these inter-related conditions. Our findings of reported diarrhoea rates being high among young children compared with national data are therefore expected; (Komarulzaman et al., 2017) diarrhoea rates for children < 5 years were substantially higher than national rates (5·1 vs 3·7 episodes per child per year). The most recent national Indonesian survey showed rates of diarrhoea, fever and respiratory illness in the two weeks prior to the survey of 14%, 31% and 4% among children < 5 years, (BPS Makassar Municipality, 2020) albeit these findings are not directly comparable with our results because of differing recall periods, study designs and survey instruments. Additionally, compared with 17·6% anaemia, 9-35·6% stunting, 8·1-28·0.9% underweight and 10·5-12·1% wasting in previous urban Indonesian studies among children, (Sandjaja et al., 2013; Semba et al., 2009; Otsuka et al., 2019) our findings of 26·5% anaemia prevalence, 44·3% stunting, 41·1% underweight, and 12·4% wasting further demonstrate the poor prevailing health conditions resulting from unsafe sanitation, flooding, and the built environment. Our results broadly align with global data on child health in urban informal settlements, which, for example, have reported both anaemia and stunting rates that are generally between 25 and 45%. (Assaf and Juan, 2020)

Disease vectors (mosquitos and small mammals) were also common and widespread. Mosquitos represent a risk factor for diseases such as dengue. Small mammals are potential vectors for diseases such as leptospirosis, and additionally are capable of transferring contaminants from sediments and environmental waters onto household surfaces. The fragile built environment, coupled with climatic conditions, creates local conditions that pose health and safety risks for occupants, particularly the potential for higher vulnerability to heat-related illness in these settlements. (Ramsay et al.)

4.1. Towards a planetary health model

The findings support both the idea that human–environmental risks are complex and multi-dimensional, and that capturing individual and interacting risk indicators through a planetary health systems approach could add value to understanding the relationships between factors that shape human health and wellbeing in urban informal settlements. Therefore, to broaden the lens traditionally applied to faecal-oral exposure pathways, and to bring together the unique datasets and results presented above, we propose a conceptual planetary health model of health and environment for urban informal settlements (Fig. 4).

The model is structured across four nested *spatial* scales: (i) the individual, (ii) house/household, (iii) settlement, and the (iv) city and beyond; and across four *thematic* domains: (1) the physical/built environment; (2) the ecological environment; (3) human health; and (4) socio-economic wellbeing (Fig. 4). Combining the spatial scale with planetary health thematic domains enables a broader array of key risk indicators and causal pathways to be explicated and linked than existing models allow.

Within the environment and human health domains, the model builds off the established microbiological 'F-diagram' model (faeces, fields, fluids, flies, food and fomites) upon which most WASH research and practice is founded. (Wagner and Lanoix, 1958; Cairncross et al., 2010) The model combines the empirical data described in this paper with other relevant models, including the Integrated Behaviour Model for WASH (Dreibelbis et al., 2013) as well as contemporary WASH scientific literature, practice frameworks, and evaluation methods (Mensah, 2020; Raj et al., 2020) (Fig. 4). Our model emphasises the role of ecological domain variables such as the thermal environment, vectors, animal faeces, (Penakalapati et al., 2017) and biodiversity, as upstream contributors to the interactions within the exposure pathways of the F diagram.

Similarly, within the physical/built environment domain at the settlement scale, the model emphasises upstream causal pathway variables that are distinctive to urban contexts. (Friesen et al., 2020) These include settlement and precinct flooding, (Cooperative Research Centre for Water Sensitive Cities, 2018) housing quality and density, (Sharpe et al., 2018) drainage, solid/hard waste, urban agriculture, (Robb et al., 2017) and land tenure, (Corburn et al., 2019) which shape exposure and risk profiles within high-density urban informal settlements. The socio-economic wellbeing domain variables include collective efficacy, (Turley et al., 2013; Sinharoy et al., 2019) gender norms/relations, (Ezbakhe et al., 2019; Winter et al., 2019) and household assets and livelihoods, key variables that have been shown to affect WASH intervention uptake and sustained behavioural change, as articulated in the IBM-WASH model. (Dreibelbis et al., 2013)

This model enables the interrogation of specific indicators and the connections and inter-relationships between them across time (e.g. seasonal effects) and space (e.g. variability within and across settlements). It is a first step towards building a composite framework of markers to examine their inter-connections and as mentioned above, eventually, their respective impact. Investigating these associations is planned in the RISE trial in order to enrich and refine the model as more data become available.

The baseline findings and our model illustrate how some markers, considered alone, could be misleading as a means to characterise urban informal settlement environments and their populations. For example, as the empirical data show, these settlements have comparable rates of open defecation and 80% have a toilet inside their home (Fig. 1). However, levels of *E. coli* in sediment and water were high, likely because no toilets were connected to safe disposal mechanisms, such as a piped sewerage network or safe septic tanks, and the sites are flood prone (Fig. 2). Human faecal waste is therefore likely to be contributing to contamination of the immediate environment. This highlights the need for data capture that extends beyond traditional measures of open defecation or markers of upgraded sanitation, instead explicitly considering the potential exposure pathways between faecal waste, environmental contamination, and flooding, across the individual, household and settlement spatial scales in the model. (Contreras and Eisenberg, 2019)

The model can also inform the design of interventions using a systems-level framework of opportunities to reduce environmental faecal contamination and to interrupt faecal–oral transmission routes. This suggests a need for interventions beyond traditional household-level WASH approaches, to systematically interrupt contamination at the precinct/catchment scale, improving accessibility, drainage, and land tenure, and ensuring safe settlement-level disposal from toilet facilities.

A limitation of this model is that it prioritises microbial contamination as it relates to water and sanitation health impacts. We acknowledge other environmental factors also affect physical health and general wellbeing outcomes (i.e. chemical contamination, air pollution), which are worthy of future research to refine the model. Also, we acknowledge the 'city and beyond' spatial scale is less articulated than the other three spatial scales, however it is included given its importance on urban

informal settlement planetary health conditions (i.e. municipal governance, urban planning) (Fuente and Bartram, 2018) and to signal an area worthy of future research. An additional limitation of our model is it may not (yet) capture all the local context-specific cultural and environmental factors that impact on morbidity, but in time this can be further developed for varying contexts across informal settlements both within and beyond single geographical locations.

To conclude, our model provides a framework for deconstructing interacting environmental, human and socioecological to ensure that the outcomes of built interventions and other mitigation actions can be adequately assessed in an integrated setting. The construction of any such model begins with site-specific information as is the case here. Thereafter, assessments of the conceptual model in other settings are required to ascertain its transferability. RISE provides one means of

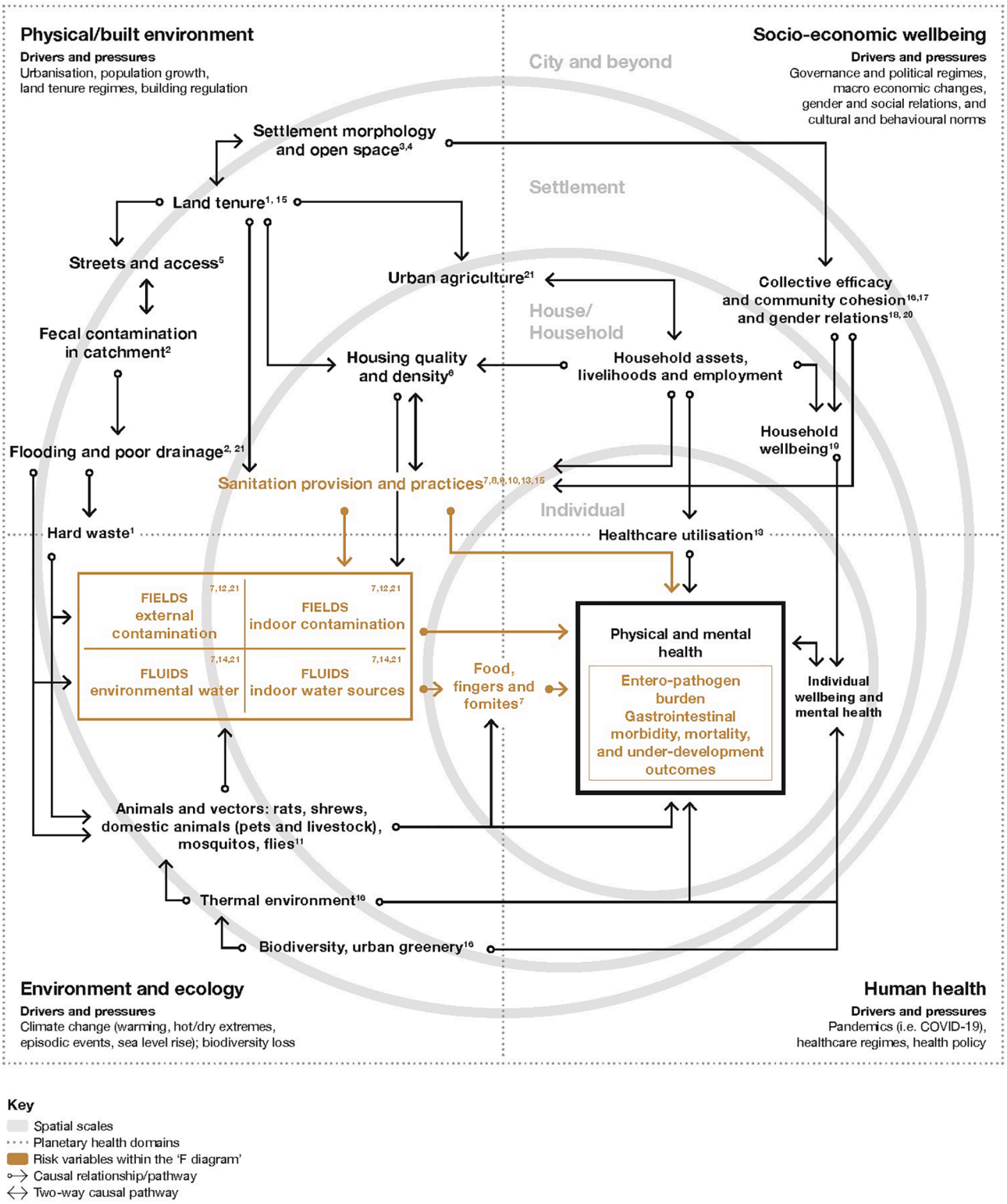

Fig. 4. A planetary health model of health and environment in urban informal settlements.

doing this as a consequence of the simultaneous investigation of another suite of sites in Suva, Fiji. (Leder et al., 2021) Multiple such assessments, across different settings globally, will enable refinement of the model such that it acquires greater generality, ultimately establishing a generalised framework useful across a wide range of settings. In this way, our model responds explicitly to planetary health's call for whole-of-systems, transdisciplinary approaches that link human and environmental health to better understand complex urban socio-ecological systems. Combining our 12-month field data with existing literature, conceptual models, and WASH practice frameworks, we have generated a conceptual model of faecal contaminant exposure in urban informal settlements that attempts to account for a wider variety of risks affecting both faecal-oral exposures and more holistic health outcomes. The model positions water and sanitation deficits within a broader framework of conditions extending beyond traditional individual- and household-level pathways of microbiological contamination. Many of the risk factors in our model are likely to be exacerbated by global climate change (Satterthwaite et al., 2020) and COVID-19, (French et al., 2020) which makes achieving targets under the Sustainable Development Goals by 2030 both more challenging and more important. (UN-Habitat, 2020)

In designing and implementing this study, we have also developed and tested a novel surveillance approach for undertaking empirical planetary health research in urban informal settlements for which there are no clear precedents. The empirical results provide a rigorous baseline to measure the effects of the RISE intervention within the RCT framework, as well as to monitor changes longitudinally over the next five years of the trial period. The model will be further tested, refined and advanced as more empirical data becomes available from the RISE trial.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2021.106679.

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