Groundwater quality studies in urban areas

Introduction

Urbanisation processes are the cause of extensive but essentially diffuse pollution of groundwater by nitrogen and sulphur compounds, salinity as well as pathogenic bacteria, protozoa and viruses (Morris et al., 2003). Household attitudes to hazards posed by drinking water can enhance quality problems with poor water treatment, types of drinking water vessels, hand washing practices, perceptions of safe water quality using only visual parameters (normally clarity of the water), and knowledge on waste disposal practices (Kioko et al., 2012).

This section firstly reviews a wide range of water quality studies in urban and peri-urban settings in SSA (n=44) assessing the impacts of urbanisation on groundwater quality, these are summarised in Table 7.1. Summary statistics, across all 44 studies for more commonly analysed water quality indicators have been summarised by in Figure 7.1. The second section then reviews case studies (n=16) focussed on the impact of on-site sanitation, principally pit latrines, on groundwater quality, these are summarised in Table 7.2. Targeted studies focused on non-sanitary sources of contamination such as industries, historical mining legacy and waste dumps/landfills are shown in Table 7.3. Key details and conclusions from these studies are summarised and critically reviewed. A hand full of case studies include both specific assessments of impacts of pit latrines as well as broader environmental hygiene considerations in spring catchments and well capture zones and are included in both Table 7.1 and 7.2.

Overall, compared to other regions globally there have been relatively few studies carried out in SSA. The review draws on studies published in books, research articles and reports, and it is recognised that these have been published for a range of purposes. With this in mind, the studies can be categorised into two broad groups. The first being short case-studies presenting data from a limited number of groundwater sites (n<20), limited temporal resolution as a single survey or use only basic chemical indicators (n<3). The second being examples which either draw from larger data sets or include both chemical and microbiological indicators or have greater temporal resolution.

Figure 7.1 Summary statistics for common water quality indicators across 44 studies included in Table 7.1. Units for values on x-axis (log scale): a=counts/100 mL, b=μs.cm⁻¹ and c=mg/L.

Table 7.1 Groundwater quality surveys in Sub-Saharan urban and peri-urban areas (n=44).

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<th>Selected results for TTC, TC, FC, (mg/L) for inorganic chemistry</th>
<th>Sampling frame</th>
<th>Conclusion and sources of contamination</th>
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Reference
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<thead>
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<th>Location</th>
<th>Layer Type</th>
<th>Wells (N)</th>
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<th><strong>Mod.wells</strong></th>
<th><strong>Trad. wells</strong></th>
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<tbody>
<tr>
<td>Dakar, Senegal</td>
<td>Quaternary</td>
<td>56</td>
<td>NO₃ 0-122</td>
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<td></td>
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<tr>
<td>Conakry, Guinea</td>
<td>Volcanic rocks, fissured</td>
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<tr>
<td>Various, Ivory coast</td>
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<td>230</td>
<td></td>
<td>NO₃ mean 69</td>
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</tr>
<tr>
<td>Bolama City, Guinea Bissau</td>
<td>Sandy soils and Cenozoic — Modern sediments</td>
<td>28</td>
<td>Dug wells in</td>
<td>Fecal Enterococci 0-850, mean 74</td>
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</tr>
<tr>
<td>Cotonou, Benin</td>
<td>Quaternary to mid Pleistocene sandstone</td>
<td>28</td>
<td>Dug wells in</td>
<td>Mn 0.06-0.19</td>
<td></td>
</tr>
<tr>
<td>Kumasi, Ghana</td>
<td>Precambrian Basement</td>
<td>10</td>
<td>Dug wells in</td>
<td>NO₃ 0.0-968</td>
<td></td>
</tr>
<tr>
<td>Kumasi, Ghana</td>
<td>Precambrian Basement</td>
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<td>Hand-dug wells</td>
<td>PO₄ &lt;0.05-21.6</td>
<td></td>
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<td>Niamey, Niger</td>
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<td>Benin City, Nigeria</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Calabar, Nigeria</td>
<td>Tertiary to recent sands and gravels</td>
<td>20</td>
<td>BOD 0.04-4.09, mean 1.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ibadan, Nigeria</td>
<td>Basement, banded gneiss and schist</td>
<td>10</td>
<td>TSS 159-186.6, mean 174</td>
<td></td>
<td></td>
</tr>
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</table>

**Fountain Analysis**
- TC 0–39
- FC 0–28
- FS 0–2
- NO₂ 0–2.5
- NH₄ 0–0.05
- Cl 1.2–1.8
- F 0–0.05
- Turb. 0.9–6.1

**Mod.well Analysis**
- TC nd
- FC 370–1x10⁴
- FS 90–9x10³
- NO₂ 2–46
- NH₄ 0.06–7
- Cl 17–130
- F 0–0.16
- Turb. 1–70

**Trad. well Analysis**
- TC nd
- FC 50–2 x10⁶
- FS 150–2 x10⁹
- NO₂ 0–71
- NH₄ 0.01–6
- Cl 8–284
- F 0.038
- Turb. 1–63

**Water Quality Results**
- **Nitrates**: Contamination from point-source seepage in urban areas
- **Wastewater**: Widespread contamination by nitrate and FC linked to poor sanitation and well construction
- **High Nitrate**: High nitrate (up to 200 mg/L) linked to domestic pollution and deforestation
- **High P and K**: High P and K concentrations in urban aquifers linked to anthropogenic pollution
- **Poor Quality**: Poor quality water quality survey showed that water quality parameters were within WHO drinking water guideline values
- **Contamination**: Contamination found even in deeper sites up to 10 mg/L, source of loading (6°N) linked to rapid urbanisation (latrines) and deforestation
- **Evidence**: Evidence of anthropogenic impact on water quality degradation
- **Single survey**: Elevated Pb, Cr, Cd and Zn attributed to indiscriminate waste disposal and FC occurrence linked to PL, soak-aways and septic tanks
- **Single survey**: FC, nitrate and Cl had a positive correlation with urbanisation
- **Dry season**: Gross pollution of groundwater attributed to poor well construction, PL and waste management

**Other Information**
- **N/A**: Samples not available
- **Mean**: Mean results
- **Dry season**: Dry season
- **Waste disposal**: Point-source contamination from PL and refuse tips as well as septic tanks linked to poor sanitation and well construction
- **Debris (FC)**: Some debris (FC) linked to proximity to PL and refuse tips as well as septic tanks linked to poor sanitation and well construction
- **TDS**: TDS 6–230, mean 113
- **NO₂**: NO₃ 0–968, mean 0.16
- **PO₄**: PO₄ 0.67–15, mean 7.8
- **TC and EC**: TC and EC <20
- **TH**: TH 8–103, mean 54
- **Fe**: Fe 0.001-0.955
- **Zn**: Zn 0.96–7.19
- **Cr**: Cr 0.02–1.1
- **Cd**: Cd Nd–0.23
- **Ni**:
- **Sb**:
- **As**: 1.2–1.8
- **Cu**:
- **Pb**:
- **Cd**: 0.005–0.074
- **Mn**: 0.01–8
- **Fe**: 0.001–0.955
- **Zn**: 0.98–7.19
- **Pb**: 0.03–0.25
- **SO₄**: 34
- **Cl**: 1.1–10, mean 5
- **TSS**: 159-186.6, mean 174
- **TC**: 2300–9200, mean 5120
- **TC**: 340–9200, mean 5120
- **Cl**: 173–1000
- **SO₄**: 211–300
- **Cl**: 370–1x10⁴
- **NO₂**: 90–9x10³
- **NH₄**: 0.06–7
- **Cl**: 17–130
- **F**: 0–0.16
- **Turb.**: 0.9–6.1
- **TC**: 370–1x10⁴
- **FS**: 90–9x10³
- **NO₂**: 2–46
- **NH₄**: 0.06–7
- **Cl**: 17–130
- **F**: 0–0.16
- **Turb.**: 1–70
- **TC**: 50–2 x10⁶
- **FS**: 150–2 x10⁹
- **NO₂**: 0–71
- **NH₄**: 0.01–6
- **Cl**: 8–284
- **F**: 0.038
- **Turb.**: 1–63

**Survey Data**
- **Dry season**: April–May 1994
- **July–October**: 1997
- **1981 and 1982**: N/A
- **July 2006**: N/A
- **May 1991, August 1991 and April 1992**: N/A
- **Monthly between Dec 2000 and Jan 2001**: N/A
- **Monthly between July 1989 and April 1990**: N/A
- **April 1990**: N/A
- **Jan 2001**: N/A
- **N/A**: N/A
- **Monthly between April–May 1991, May 1991, and July 2006**: N/A

**References**
- Cissé Faye et al. (2004)
- Gélinas et al. (1998b)
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- Boukari et al. (1996)
- Boukari et al. (2007)
- Nkansah et al. (2010)
- Obiri-Danso et al. (2009)
- Girard and Hillaire-Marcel (1997)
- Malomo et al. (1990)
- Erah and Akujieze (2002)
- Eni et al. (2011)
- Ochieng et al. (2011)
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<td>Dug wells</td>
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<tr>
<td>Iboqun, Pakoto, Ifo, Ogun State, Nigeria</td>
<td>Cambrian basement geology and weathered regolith</td>
<td>Wells and boreholes in a middle class area</td>
<td>July-August 2009</td>
<td>Adelekan (2010)</td>
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<tr>
<td>Abeokuta, Nigeria</td>
<td>Basement igneous and metamorphic</td>
<td>All bacterial count&gt;20</td>
<td>December 2005</td>
<td>Olabisi et al. (2008)</td>
</tr>
<tr>
<td>Urban &amp; peri-urban area, Abeokuta, Nigeria</td>
<td>Basement igneous and metamorphic</td>
<td>Shallow wells</td>
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<tr>
<td>Pert-urban area, Abeokuta, Nigeria</td>
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<td>Warri River plain, Delta, Nigeria</td>
<td>Alluvial Benin formation</td>
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<td>Calabar, Nigeria</td>
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<td>Masaka, Nigeria</td>
<td>Cretaceous sandstone and clay</td>
<td>Dug wells, high density</td>
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<td>Yaounde, Cameroon</td>
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<td>Springs and wells in high density area</td>
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<td>Douala, Cameroon</td>
<td>Alluvium over Pliocene sand and gravel</td>
<td>Springs, wells and boreholes</td>
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</table>

**Water Quality Analysis:**
- **Survey to August 2004:** Survey to determine water quality.
- **July-August 2009:** Analysis of water quality during the rainy season.
- **July 2009:** Analysis of water quality in relation to seasonal changes.
- **December 2005:** Analysis of water quality for the month.
- **Dry season:** Analysis of water quality during the dry season.
- **Rainy season 2008:** Analysis of water quality during the rainy season.
- **2 year sampling campaign:** Analysis of water quality over a 2-year period.
- **Wet and dry season July-Dec 1999:** Analysis of water quality during wet and dry seasons.
- **Samples taken in wet season but not during rainfall events to avoid contamination from surface runoff:** Analysis of water quality during the wet season excluding rainfall events.

**References:**
- Takem et al. (2010)
- Ewodo et al. (2009)
- Alhassan and Ujah (2011)
- Ugbaja and Edet (2004)
- Orebiyi et al. (2010)
- Taiwo et al. (2011)
- Ibhe and Agbamu (1999)
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<tr>
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<td>Wells including sanitary survey</td>
<td>Monthly between February-March 2004 to September 2005</td>
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<td>Mekelle, Ethiopia</td>
<td>Mesozoic sediments</td>
<td>Wells, springs and boreholes (100)</td>
<td>Wet season, TDS 200-710 NO₃⁻, NO₂⁻, PO₄³⁻, PH, TH</td>
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<td>Bahir Dar, Ethiopia</td>
<td>Weathered and fractured Alkaline Basalt</td>
<td>Dug wells and protected pumps in inner, middle and outer zones (8)</td>
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</tr>
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<td>Addis Ababa, Ethiopia</td>
<td>Volcanics</td>
<td>Boreholes and springs (9)</td>
<td>Various</td>
</tr>
<tr>
<td>Addis Ababa, Ethiopia</td>
<td>Volcanics</td>
<td>Springs and boreholes (10)</td>
<td>2002</td>
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<tr>
<td>Addis Ababa, Ethiopia</td>
<td>Volcanics</td>
<td>Springs and wells (63)</td>
<td>Urban area, leaching from polluted soils.</td>
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<td>Quaternary/Basementgneiss-granite complex</td>
<td>Hand dug wells: Timbuktu (31), Lichinga (159)</td>
<td>Contamination of groundwater sources from on site sanitation traced using N:Cl</td>
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<td>Kampala, Uganda</td>
<td>Weathered Basement</td>
<td>Wells and springs</td>
<td>Contrasting hydrological conditions</td>
</tr>
</tbody>
</table>

**Table Values:**

- **Dry season**
  - TDS: 180–450
  - NO₃⁻, NO₂⁻, PO₄³⁻, PH, TH
- **Wet season**
  - TDS: 200–710
  - NO₃⁻, NO₂⁻, PO₄³⁻, PH, TH
- **Middle and inner city**
  - TDS: 20–600
  - NO₃⁻, NO₂⁻, PO₄³⁻, PH, TH
- **Outer city**
  - TDS: 20–70
  - NO₃⁻, NO₂⁻, PO₄³⁻, PH, TH

**Water Quality Parameters:**

- **Kinshasa, DR Congo**
  - Alk: 8–41
  - NO₃⁻: 0.72–35
  - NO₂⁻: <0.01
  - COD: 6.8–41
  - Alk: 8–41
  - NH₄⁺: 0–12
  - Cl: 46–270
  - FC: 93%
- **Mekelle, Ethiopia**
  - Zn: 0.87–146
  - Ni: 0.31–0.98
  - Cu: 0.44–1.82
  - Pb: 0.36–56.2
  - Cd: <0.1–0.2
  - Co: <0.1–9.12
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**References:**

- [Barrett et al., 2011](#)
- [Cronin et al., 2013](#)
- [Akoma (2011)](#)
- [Goshu et al., 2010](#)
- [Goshu and Akoma, 2011](#)
- [Abiye (2008)](#)
- [Alemayehu (2006)](#)
- [Denlie and Wohlhnh (2006)](#)
- [Cronin et al. (2007)](#)
- [Barrett et al. (1998)](#)
- [Howard et al. (2003)](#)
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<th>Water Quality Variables</th>
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<td>Monitoring wells (16)</td>
<td>Dry season: SEC 272-345, P BDL-0.11, Cl 31-50.5, TC 0-131, FC 0-35; Wet season: SEC 280-372, P BDL0.04, Cl 28-192, TC 29-10000, FC 6-8300</td>
<td>Broad hydrochemistry suite including key water quality variables: SEC 200-710, NO&lt;sub&gt;3&lt;/sub&gt; &lt;0.1-43, NH&lt;sub&gt;4&lt;/sub&gt; &lt;0.25-3.5, Cl 4.6-36, PO&lt;sub&gt;4&lt;/sub&gt; &lt;0.1-4, B &lt;1-10, Pb 0.14-0.67, Hg &lt;0.4-13</td>
</tr>
<tr>
<td>Lusaka, Zambia</td>
<td>Dolomite</td>
<td>Wells and streams in intensely urbanised area (9)</td>
<td>Dry season: SEC 272–345, P BDL–0.11, Cl 31–50.5, TC 0–131, FC 0–35; Wet season: SEC 280–372, P BDL0.04, Cl 28–192, TC 29–10000, FC 6–8300</td>
<td>Values for nitrate and Hg were in excess of WHO standards on some occasions. Poor sanitation and solid waste disposal implicated.</td>
</tr>
<tr>
<td>Lusaka province, Zambia</td>
<td>Dolomite</td>
<td>Boreholes and wells (28)</td>
<td>Dry season: SEC 210–330, Cl 21–35, Fe 0.1–0.8, FC 0–5200, FS 0–640; Wet season: SEC 306–383, Cl 14–29, Fe 0.4–0.7, FC 0–11 000, FS 0–7000</td>
<td>Various: 1995-2000 Groundwaters highly contaminated due to poor sanitation and domestic waste disposal. 58% of residence use traditional PL.</td>
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<td>South Lunzu, Blantyre, Malawi</td>
<td>Precambrian Basement</td>
<td>Borehole, springs and dug well (9)</td>
<td>Dry season: SEC 210–330, Cl 21–35, Fe 0.1–0.8, FC 0–5200, FS 0–640; Wet and dry season on two occasions</td>
<td>Wet and dry season (26) Contamination levels higher during wet season Widespread drinking water contaminated with FC and concerns over Pb from pump materials.</td>
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<td>Southern Malawi</td>
<td>Weathered basement</td>
<td>Shallow wells</td>
<td>Dry season: SEC 210-330, Cl 21-35, Fe 0-1-0.8, FC 0-5200, FS 0-640; Wet and dry season (26)</td>
<td>Wet and dry season (26) Contamination levels higher during wet season.</td>
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<td>Tamatave and Foulpointe, Madagascar</td>
<td>Weathered basement and unconsolidated sediments</td>
<td>Boreholes (53)</td>
<td>Dry season: SEC 70-100, NO&lt;sub&gt;3&lt;/sub&gt; 4.4-35, mean 23 Pb 1-215, mean ca.5</td>
<td>Single study High nitrate (&gt;100 mg/L) common in groundwater. Likely sources identified as sewage effluents. The occurrence of E. coli VG in source water was important for transmission. Significant correlation with turbidity.</td>
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<td>Dodomo, Tanzania</td>
<td>Basement</td>
<td>Wells, boreholes and springs</td>
<td>Dry season: SEC 70-100, NO&lt;sub&gt;3&lt;/sub&gt; 4.4-35, mean 23 Pb 1-215, mean ca.5</td>
<td>Single study</td>
</tr>
<tr>
<td>Bagamaoyo, Tanzania</td>
<td>Unconsolidated sediments</td>
<td>Shallow wells and boreholes</td>
<td>Entovirus detected in 1% Rotavirus 4% E. Coli virulence genes 42% Human specific Bacteriodales marker 4% Turbidity</td>
<td>Single study</td>
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Table 7.2  Studies investigating groundwater contamination from pit latrines (n=16).

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<td>Sandy soils</td>
<td>Installed test wells (17)</td>
<td>Ammonium, nitrate, turbidity, pH, Conductivity, TC, FC</td>
<td>Feb–May 2005</td>
<td>Low FC &gt;5 m from PL, N conc. usually below WHO standards</td>
<td>Dzwairo et al. (2006)</td>
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<tr>
<td>Epworth, Zimbabwe (urban)</td>
<td>N/A</td>
<td>New and existing wells (28)</td>
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<td>N/A</td>
<td>Elevated N and Coliforms in most of study area</td>
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<td>Fine-course sands</td>
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<td>June–July</td>
<td>High contamination &lt;11 m from PL</td>
<td>Vinger et al. (2012)</td>
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</tbody>
</table>

SEC-specific electrical conductivity, TDS- total dissolved solids, TH-total hardness, BOD-biological oxygen demand, COD-chemical oxygen demand, FC-faecal coliforms, EC-E. Coli, TC-total coliforms, FS-faecal streptococcus. Microbiological units as cfc/100 mL unless stated otherwise, TNCT-too numerous to count, BDL-below detection limit.
<table>
<thead>
<tr>
<th>Location</th>
<th>Geology</th>
<th>Methodology</th>
<th>Parameters</th>
<th>Results</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mbazwana, South Africa (urban)</td>
<td>Sands</td>
<td>Installed test wells (5)</td>
<td>FC and nitrate</td>
<td>Bimonthly 2000–2002 Low nitrate (&lt;10 mg/L) and FC (&lt;10/100 mL) &gt;1 m from PL</td>
<td>Still and Nash (2002)</td>
</tr>
<tr>
<td>Botswana, Mochudi/Ramotswa</td>
<td>Well-poorly drained soils</td>
<td>Existing wells (&gt;60)</td>
<td>P, N, stable isotopes and Cl</td>
<td>N/A Variable N leaching from PL</td>
<td>Lagerstedt et al. (1994)</td>
</tr>
<tr>
<td>Botswana (rural)</td>
<td>Clayey soils and fissured geology</td>
<td>Existing well and observation well (2)</td>
<td>Broad Hydrochemistry, E. coli</td>
<td>October–February 1977 Contamination of wells near latrine with E. Coli and nitrate</td>
<td>Lewis et al. (1980)</td>
</tr>
<tr>
<td>Various, Benin (rural)</td>
<td>N/A</td>
<td>Existing wells (225)</td>
<td>Andenovirus, rotavirus</td>
<td>Wet/dry season 2003–2007 Viral contamination n linked to PL proximity</td>
<td>Verbeyen et al. (2009)</td>
</tr>
<tr>
<td>Langas, Kenya (urban)</td>
<td>N/A</td>
<td>Existing wells (35)</td>
<td>TC, FC</td>
<td>January–June 1999 Widespread well contamination linked to PL and other waste sources</td>
<td>Kimani-Murage and Ngindu (2007)</td>
</tr>
<tr>
<td>Kisumu, Kenya (urban)</td>
<td>N/A</td>
<td>Existing wells (191)</td>
<td>FC, nitrate, Cl, F</td>
<td>1998 to 2004 Groundwaters highly contaminated due to poor sanitation and domestic waste disposal. 58% of residents use traditional PL</td>
<td>Wright et al. (2012)</td>
</tr>
<tr>
<td>South Lunzu, Blantyre, Malawi</td>
<td>Precambrian Basement</td>
<td>Borehole, springs and dug well (4)</td>
<td>SEC, Cl, Fe, FC, FS</td>
<td>Wet and dry season on two occasions</td>
<td>Palamuleni (2002)</td>
</tr>
<tr>
<td>Uganda, Kampala (urban)</td>
<td>Karstic geology</td>
<td>Installed wells and spring (17)</td>
<td>Conductivity, pH, P, nitrate, Cl, FC and FS</td>
<td>March–August 2003, weekly and monthly Widespread well contamination linked to PL and other waste sources Widespread contamination from PL and poor animal husbandry, both protected and unprotected sources unfit for drinking</td>
<td>Kulobako et al. (2007)</td>
</tr>
<tr>
<td>Uganda, Kampala (urban)</td>
<td>Karstic geology</td>
<td>Springs (4)</td>
<td>FC, FS., nitrate, ammonium</td>
<td>Wet and dry season for 5 consecutive weeks</td>
<td>Nsubuga et al. (2004)</td>
</tr>
</tbody>
</table>
Howard et al. (2003)\[36\]

PL = Pit latrine, FC = Fecal coliform, TC = Total coliform, FS = Fecal strep. Concentrations in mg/L unless otherwise stated.

Table 7.3 Studies focused on impacts of non-sanitary sources on groundwater quality.

<table>
<thead>
<tr>
<th>Area/Country</th>
<th>Geology</th>
<th>Sample sites</th>
<th>Results (mg/L)</th>
<th>Sources</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uganda, Kampala (urban)</td>
<td>Karstic sediments Springs (25)</td>
<td>FC, FS Monthly September 1998–March 1999 Spring contamination linked to local environmental hygiene and completion rather than on-site sanitation</td>
<td>Howard et al. (2003)[36]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Akure, Nigeria</td>
<td>Basement</td>
<td>Boreholes in landfill vicinity</td>
<td>TDS 18–342&lt;br&gt;TH 136-140&lt;br&gt;NO$_3$ 30–61&lt;br&gt;Fe 0.9-1.4&lt;br&gt;Pb 0–1.21&lt;br&gt;Zn 0–2.3&lt;br&gt;Cr 0–0.25</td>
<td>Landfill values decrease with distance 50–100 m&lt;br&gt;Industrial areas and landfill, Sites within 2 km radius of landfill affected.</td>
<td>Akinbile and Yusoff (2011)[59]</td>
</tr>
<tr>
<td>Ojota, Lagos, Nigeria</td>
<td>Sedimentary</td>
<td>10 boreholes, 10 dug wells</td>
<td>SEC 68–3030, mean 584 μS/cm &lt;br&gt;Fe 0–21.4, mean 4.23 &lt;br&gt;Cu 0–33, mean 0.02 &lt;br&gt;Pb 0–14.8, mean 2.4 &lt;br&gt;Zn 0–0.23, mean 0.04</td>
<td></td>
<td>Oyeku and Eludoyin (2010)[60]</td>
</tr>
<tr>
<td>Igando, Lagos, Nigeria</td>
<td>Sedimentary</td>
<td>Wells 10–375 m from landfill</td>
<td>TDS 3–23, mean 9.0 &lt;br&gt;NO$_3$ 17.4–60.5, mean 38.5 &lt;br&gt;NH$_4$ 0.12–0.3, mean 0.22 &lt;br&gt;PO$_4$ 7.07–15.12, mean 10.7</td>
<td>Municipal landfill</td>
<td>Longe and Balogun (2009)[61]</td>
</tr>
<tr>
<td>Ibadan, Nigeria</td>
<td>Basement</td>
<td>Soil and groundwater</td>
<td>Cd 0.01 &lt;br&gt;Cr, Pb, Co, Ni not detected</td>
<td>Adelekan and Alawode (2011)[62]</td>
<td></td>
</tr>
<tr>
<td>Ilorin, Nigeria</td>
<td>Basement</td>
<td></td>
<td>Colour, turbidity over WHO limit EC 161-731&lt;br&gt;TH 37-153&lt;br&gt;TC 1600–&gt;1800 &lt;br&gt;</td>
<td>Industrial estate</td>
<td>Adekunle (2009)[63]</td>
</tr>
<tr>
<td>Location</td>
<td>Rock Type</td>
<td>Geologic Setting</td>
<td>Wells and Springs</td>
<td>Dry Up gradient</td>
<td>Wet Up gradient</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>--------------------</td>
<td>------------------------</td>
<td>--------------------------------------------------</td>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Dar-es-Salaam, Tanzania</td>
<td>Sedimentary, Sandstones</td>
<td>Wells up and down gradient</td>
<td>gobed {Mn 0.03 Mn 0.00}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lokpaukwu, Lekwesi and Ishiagu, Nigeria</td>
<td>Shales and igneous intrusions</td>
<td>Springs and open dug wells</td>
<td>gobed {Mn 0.02 Mn 0.05}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lusaka and Copperbelt, Zambia</td>
<td>Sedimentary, Dolomite</td>
<td>Surface and groundwater</td>
<td>gobed {Mn 0.00 Mn 0.12}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It is clear from looking at the studies in the published literature that there have been particular concerns related to groundwater quality in southern Nigeria, which account for about 30% of the published studies. These studies are located near Lagos and Abeokuta in the south west, the Delta area in the south and Calabar, and there are additional concerns over pollution from the oil industry in parts of southern Nigeria. Other notable examples of urban areas that have a number of studies include Lusaka in Zambia, Dakar in Senegal, Addis Ababa in Ethiopia and Kampala in Uganda.

**Impacts of urbanisation**
Chemical and physical indicators of groundwater quality degradation

Physical indicators

Total dissolved solids (TDS) or specific electrical conductivity (SEC) are the most commonly applied physical water quality indicators in groundwater studies and are often used in combination with more specific indicators such as dissolved chemistry or microbiology (see Table 7.1). They have a major advantage of being field methods, which are easy to use and versatile, enabling the user to carry out a crude assessment of water quality rapidly and with minimal cost. The baseline quality of groundwater, with relatively low total dissolved solids (TDS), makes TDS a good indicator of contaminant loading. Many studies also use hardness or field alkalinity in the same manner, as these are also indicative of contaminant loading and have many of the benefits outlined above. Geophysical methods such as electrical resistivity tomography (ERT) are also valuable for characterising subsurface contamination from landfills and sites with historical industrial pollution as well as saline intrusion induced by abstraction (Loke et al., 2013[66]; Martínez et al., 2009[67]). However, these are costly systems to deploy there are only a limited number of studies that have used these techniques for assessing groundwater contamination in urban SSA, with the majority of the studies being from South Africa and Nigeria (Akankpo, 2011[68]; Ehirim et al., 2009[69]; Silliman et al., 2010[70]).

Nitrate and chloride

Nitrate and chloride are the most widely used water quality indicators of anthropogenic pollution. Nitrate data has been reported in over 80% of the groundwater studies summarised in Table 7.1. Relatively simple sample preservation and analysis required makes these parameters attractive for initial water quality screening. Nitrate concentrations ranged from Below Detection Level (BDL) to >500 mg/L (as NO₃⁻), although typical maximum concentrations were generally below 150 mg/L. The WHO guideline value for nitrate is 50 mg/L as NO₃⁻. The WHO has not published a health-based guideline for chloride, but suggests that concentrations over 250 mg/l can give rise to a detectable taste.

Both tracers have been used in a broad range of geologic and climate zones to investigate pollution from on-site sanitation, waste dumps, as well as urban agriculture (Table 7.3). Nitrate concentrations show a high degree of variability both within studies and between studies that have been reviewed. Two principle factors that affect nitrate occurrence are firstly the prevailing redox conditions in groundwater, and secondly the residence time and vulnerability of the groundwater body. There are several examples of low nitrate groundwater in Table 7.1 which show evidence of faecal contamination (Gélinas et al., 1996a[71]; Mwendera et al., 2003[72]; Nkhuwa, 2003[73]) which has implications for the potential for denitrification in shallow groundwaters. Nitrate has been used successfully to characterise urban loading to groundwater from a range of sources including pit latrines (Cissé Faye et al., 2004[74]), landfills (Ugbaja and Edet, 2004[75]; Vala et al., 2011[76]) and applied to look at impacts on groundwater quality across different population densities (Goshu and Akoma, 2011[77]; Goshu et al., 2010[78]; Orebiyi et al., 2010[79]). There are other sources of N loading to groundwater in growing urban areas including the impact of deforestations, and these have been delineated using N:Cl ratios and in a few examples by using δ¹⁵N analysis (Faillat, 1990[80]).

A series of geochemical transformations can occur in water with a high carbon loading with a progressive decline in redox potential, leading sequentially to the removal of nitrate by denitrification, the mobilisation of manganese and iron and the reduction of sulphate (Gooddy et al., 1999[81]). Borehole mixing processes can cause dilution and overall low nitrate concentrations while still having significant microbiological contamination. Lagerstedt et al. (1994)[82] and Cronin et al. (2007)[83] have successfully used NO₃⁻:Cl to fingerprint different sources of urban and peri-urban
pollution in groundwaters in SSA. This has a certain appeal due to its simplicity; however, prevailing redox conditions and mixing processes need to be considered when using this approach. Many studies have effectively used nitrate in combination with other basic physical indicators such as SEC or TDS and turbidity to assess contamination and map areas of high and low pollution.

**Ammonium and phosphate**

It is evident from the literature that only a minority of case studies (ca. 20%) contain data for NH$_4$ and close to 30% contain data for PO$_4$. In part this is due to the more involved analytical procedures for NH$_4$, the high detection limits for PO$_4$ by ion chromatography and the fact that these parameters need to be analysed rapidly after sampling to ensure valid results. The WHO have not published health-based guidelines for ammonium and phosphate, however P is often the limiting nutrient in the aquatic environment and therefore concentrations >20 mg/L are considered high in surface water bodies.

Both species are closely associated with contamination from pit latrines and leaking sewer systems. Examples of ammonium and phosphate contamination from the cities of Lusaka, Abeokuta, Calabar and Makelle are shown in Table 7.1. (Berhane and Walraevens, 2013[28]; Cidu et al., 2003[38]; Taiwo et al., 2011[43]; Ugbaja and Edet, 2004[13]). Ammonium concentrations in urban groundwater range from BDL-60 mg/L, although most case studies had maximum concentrations below 10 mg/L. The highest concentrations were reported in Lusaka, Zambia where karstic limestone aquifer which underlies much of the city and very rapid transport times in the groundwater are implicated. Both indicators do not behave conservatively in soils and groundwater, NH$_4$ is positively charged and therefore has a strong affinity for negatively charged surfaces such as clays, for this reason, as well as microbiological processing, attenuation is particularly high in the soil zone.

Phosphate concentrations range from BLD-86 mg/L, although very few studies report values >20 mg/L. Phosphate has very limited mobility in the subsurface and has a strong affinity to iron oxy-hydroxides as well as carbonates, background concentrations are usually low, e.g. <0.2 mg/L, concentrations in urban groundwater are also usually low unless there is either a very high loading or very rapid groundwater flow for example in fractured basement or karstic limestone (Cidu et al., 2003[38]; Nkansah et al., 2010[41]; Zingoni et al., 2005[45]).

**Trace elements**

Overall relatively few studies have characterised trace element contamination in urban groundwater, and studies published to date usually report results for only a handful of elements (e.g. Fe, Mn, Pb, Zn, Ni, V, Cr, Cd). This is in part due to the cost and access to suitable analytical facilities in SSA for multi-element analysis by ICP-MS or AES, and the relatively poor detection limits for some single element methods.

Studies investigating trace element concentrations have tended to be focused on non-sanitary sources, either the effect of mining (Ikenaka et al., 2010[24]; Nachiyunde, Kabunga et al., 2013[39]; Von der Heyden and New, 2004[25]) or waste dumps (Momodu and Anyakora, 2010[42]; Yusuf, 2007[15]). The main findings from these studies are summarised in Table 7.1 and there are further examples in Table 7.3. Low concentrations of Cd (0.13-0.2 mg/L) and Pb (0.04-0.09 mg/L) were reported by Vala et al. (2011)[22] in a study in Kinshasa, DRC, where groundwater was contaminated from waste dumps. Aremu et al. (2002)[22] report high Pb (0.4 mg/L) and moderate Cr (9 mg/L) and Cd (8.5 mg/L) in groundwaters from the Warri River plain in Nigeria, contamination from industry is cited as the source of contamination. Von der Heyden and New (2004)[25] reported elevated concentrations of Co, Ni and Zn down flow gradient of tailings, however concentrations were found to be below WHO drinking water quality standards in all cases, this is likely due to sulphide precipitation and natural
attenuation processes.

There have been three notable studies in Addis Ababa, Ethiopia, that have considered natural geogenic contamination within an urban context (Abiye, 2008[31]; Alemayehu, 2006[32]; Demlie and Wohnlich, 2006[33]). These studies report elevated concentrations of Zn, Ni, Pb, Cd, Co and Cr all above WHO drinking water quality standards.

Microbiological indicators of groundwater quality degradation

The importance of concentrating efforts on the control of microbial contamination of drinking water rather than chemical contamination is expressed in the WHO Guidelines for Drinking-Water Quality (WHO, 2011[76]):

‘The most common and widespread health risk associated with drinking water is microbial contamination, the consequences of which mean that its control must always be of paramount importance.’

Until relatively recently there has been a widely held misconception that groundwater was safe to drink with the minimum of treatment. The overlying soil layers were believed to provide a barrier to the transport of surface contamination to the groundwater, and that pathogenic microorganisms in particular would be removed by filtration or inactivated by sunlight, desiccation, and predation. Although this assumption may be accurate in many cases, it cannot be universally applied: it is particularly dangerous assumption when managing shallow groundwater sources of the type widely used in SSA. Hand-dug wells are widespread in urban and rural areas of SSA and are frequently poorly constructed, inadequately protected and badly maintained, making them vulnerable to contamination from pollution sources on the surface and underground. The microbiological quality of the water in these sources is often poor due to contamination by human and animal excreta.

Although the contamination of water by faeces can be measured by a number of different chemical parameters, it is a common and widespread practice to use bacterial indicators of faecal contamination as the best representative of the presence of pathogens. Of the 44 studies listed in Table 7.1, 38 have included one or more microbiological indicators in the suite of parameters that have been tested. The most widely used group of indicator bacteria in these studies is the coliform group, which includes E.coli, but some authors, for example Gelinas et al (1996)[77] and Bordalo and Savva-Bordalo (2007)[6] have also included faecal streptococci as an alternative indicator of faecal contamination. This section will briefly describe the ideas behind the use of faecal indicator bacteria, and then list the main characteristics of the two groups of indicators used in the 44 studies listed above.

Indicator concept

The main source of pathogen contamination in water is faeces. Human and animal faeces contains a high microbial load with a very diverse range of species (Leclerc et al, 2001[78]) that are derived from the normal flora of the gut. Many of the bacteria in the gut are either very difficult to culture, or cannot be cultured with the techniques currently available, so estimating the bacterial load in faeces is extremely difficult. Using methods that detect genetic material, O’Hara and Shanahan (2006)[79] have estimated between 1011 and 1012 bacteria in one gram of colonic content (60% of the faecal mass). Most of these bacteria are harmless saprophytes that colonise the gut and aid digestion, but
faeces also contains pathogenic microorganisms, and it is these that are of concern when they get into water. Table 7.4 shows the range of pathogens that have been isolated from groundwater under the different categories of bacteria, viruses and protozoa, and the diseases that they are known to cause.

<table>
<thead>
<tr>
<th>Organism</th>
<th>Disease</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Viruses</strong></td>
<td></td>
</tr>
<tr>
<td>Coxsackievirus</td>
<td>Fever; pharyngitis; rash; respiratory disease; diarrhoea; haemorrhagic</td>
</tr>
<tr>
<td></td>
<td>conjunctivitis; myocarditis; pericarditis; aseptic meningitis; encephalitis;</td>
</tr>
<tr>
<td></td>
<td>reactive insulin-dependent diabetes; hand, foot and mouth disease</td>
</tr>
<tr>
<td>Echovirus</td>
<td>Respiratory disease; aseptic meningitis; rash; fever</td>
</tr>
<tr>
<td>Norovirus</td>
<td>Gastroenteritis</td>
</tr>
<tr>
<td>Hepatitis A</td>
<td>Fever; nausea; jaundice; liver failure</td>
</tr>
<tr>
<td>Hepatitis E</td>
<td>Fever; nausea; jaundice; death</td>
</tr>
<tr>
<td>Rotavirus A and C</td>
<td>Gastroenteritis</td>
</tr>
<tr>
<td>Enteric adenovirus</td>
<td>Respiratory disease; haemorrhagic conjunctivitis; gastroenteritis</td>
</tr>
<tr>
<td>Calicivirus</td>
<td>Gastroenteritis</td>
</tr>
<tr>
<td>Astrovirus</td>
<td>Gastroenteritis</td>
</tr>
<tr>
<td><strong>Bacteria</strong></td>
<td></td>
</tr>
<tr>
<td><em>Escherichia coli</em></td>
<td>Gastroenteritis; haemolytic Uremic Syndrome (HUS, enterotoxic <em>E.coli</em>)</td>
</tr>
<tr>
<td><em>Salmonella spp.</em></td>
<td>Enterocolitis; endocarditis; meningitis; pericarditis; reactive arthritis;</td>
</tr>
<tr>
<td></td>
<td>pneumonia; typhoid fever; paratyphoid fever</td>
</tr>
<tr>
<td><em>Shigella spp.</em></td>
<td>Gastroenteritis; dysentery; reactive arthritis</td>
</tr>
<tr>
<td><em>Campylobacter jejuni</em></td>
<td>Gastroenteritis; Guillain-Barrè syndrome</td>
</tr>
<tr>
<td><em>Yersinia spp.</em></td>
<td>Diarrhoea; reactive arthritis</td>
</tr>
<tr>
<td><em>Vibrio cholera</em></td>
<td>Cholera</td>
</tr>
<tr>
<td><strong>Protozoa</strong></td>
<td></td>
</tr>
<tr>
<td><em>Cryptosporidium spp.</em></td>
<td>Diarrhoea</td>
</tr>
<tr>
<td><em>Giardia lamblia</em></td>
<td>Chronic diarrhoea</td>
</tr>
</tbody>
</table>

Ideally, drinking water quality monitoring strategies would include a screen for the major pathogens causing disease, but currently there are methodological problems that make this approach impractical. As shown in Table 7.4 there are a lot of different pathogens and each one has its own method of analysis, which can be slow and expensive. Furthermore, many of the pathogens in the three main categories cannot be cultivated using standard laboratory methods. New methods of analysis that detect nucleic acids, and which can be applied to the detection of any organism, are being introduced, but they are not yet widely available and are expensive and technically demanding. A further constraint on the direct detection of pathogens for routine monitoring is that their occurrence in water is often seasonal, with their presence coinciding with the pathogen circulating in the population (Payment and Locas, 2011[80]).

To overcome the current limitations of testing directly for pathogens in water, microbiologists have identified a small number of enteric microorganisms, universally present in faeces, that are not themselves pathogens but which can be used to indicate the potential risk of pathogens being present in the water. These microorganisms are referred to as faecal indicator organisms. The characteristics of an ideal indicator are (Payment and Locas, 2011[80]):
• Should be absent in unpolluted water and present when the source of pathogenic microorganisms of concern is present.
• Should not multiply in the environment.
• Should be present in greater numbers than the pathogenic microorganisms.
• Should respond to natural environmental conditions and water treatment processes in a manner similar to the pathogens of concern.
• Should be easy to isolate, identify, and enumerate.
• Should be inexpensive to test thereby permitting numerous samples to be taken.
• Should not be pathogenic microorganisms (to minimise the health risk to the analyst).

The coliform group of bacteria, which includes E.coli, and faecal streptococci (enterococci), are the most widely used groups of faecal indicator bacteria; however, none of them fulfil all of the characteristics of an ideal indicator and there are widely reported limitations to their use. Despite the negative publicity faced by coliforms and other faecal indicators, they are likely to continue being used in water quality monitoring programmes for the foreseeable future. This is reflected in the conclusions of a recent review of faecal indicator studies by Payment and Locas (2011) who state:

‘Fecal indicators are the best predictor of potential risk, but their concentrations rarely correlate perfectly with those of pathogens. Thus, bacterial indicators can predict the probable presence of pathogens in water, but they cannot predict precisely the level of occurrence.’

In the following sections we describe the basic characteristic of the coliform group of faecal indicators, and faecal streptococci. More comprehensive reviews of faecal indicators have been published (Ashbolt et al., 2001 [81]; Gleeson and Gray, 1997 [82]; Leclerc et al., 2001 [78]; Mesquita et al., 2013 [83]; Tallon et al., 2005 [84]).

**Total coliforms**

This is a diverse group of bacteria that share several biochemical and physiological properties. They are all Gram negative (a simple staining procedure that divides bacteria into two groups — Gram positive and Gram negative — that is determined by the cell wall structure), rod-shaped organisms. They will grow in the presence of bile salts (chemicals excreted into the gut by the gall bladder) and utilise lactose as a sugar source, producing acid and gas as metabolic by-products. They are oxidase negative and do not produce spores or other sub-cellular structures that are highly resistant to environmental stress. More recently they have been grouped according to having the enzyme β-galactosidase, which is involved in the metabolism of lactose and can be detected using a colour producing substrate. They grow at 37°C and are facultative anaerobes, which mean that they can grow in the presence and absence of oxygen using two different metabolic systems.

The total coliforms include several genera of bacteria. From early on it was discovered that several of these genera contain bacterial species that can grow in the environment in the absence of faecal contamination. Thus the isolation of total coliforms from water did not necessarily mean that the water was contaminated by faeces. In a an analysis of over 1000 strains of Enterobacteriaceae from drinking water, 51% were not of faecal origin (Gavini et al., 1985 [85]). Their role as faecal indicators, and their potential significance as a measure of health risk, was thus undermined and recently many countries have reduced their significance in the list of water quality indicators (Stevens et al., 2003...
Tables 7.1 to 7.3 above list several studies that have included total coliforms amongst the suite of microbiological parameters that have been used to measure the quality of water from a variety of sources. But given the widespread occurrence in the environment of species belonging to the total coliform group (Leclerc et al., 2001), the significance of their presence in shallow groundwater in peri-urban areas is questionable.

**Thermotolerant coliforms and escherichia coli**

Thermotolerant coliforms (sometimes referred to as faecal coliforms) are a subgroup of the total coliform group. They are differentiated from the total coliform group by their ability to grow at 44°C. The thermotolerant coliforms are much more indicative of faecal contamination than the total coliform group; however, this group still contains some genera of bacteria, particularly Klebsiella, Enterobacter and Citrobacter that can be isolated from environmental sources in the absence of faeces (Tallon et al, 2005).

The method for quantifying thermotolerant coliforms is relatively straightforward because it only requires incubation at 44°C to select for the organisms; no further selective growth steps or confirmation steps are performed on the isolates. In many laboratories in developing countries this is the limit of the resources that are available, and several of the more well-known field test kits (for example, Potalab, Delagua and Paqualab) can only be this specific. But there is a stronger justification for using TTC as an indicator of faecal contamination in drinking water than total coliforms. E.coli is the predominant species of the TTC group and constitutes over 90% of the species isolated from faeces (Tallon et al, 2005), and as much as 99% of TTC isolated from shallow groundwater in peri-urban areas (Howard et al, 2003). It is the only species in the coliform group that is exclusively associated with a faecal source (animal and human) in temperate waters. The association is not quite so clear in tropical waters, with the results of some studies suggest that E.coli can be isolated from pristine waters (Carrillo et al., 1985; Ishii and Sadowsky, 2008) and from certain industrial discharges that have not been exposed to faeces (Gauthier and Archibald, 2001). Nevertheless, E.coli is recommended as the sole indicator bacteria of recent faecal contamination (Tallon et al, 2005).

The predominance of E.coli in the TTC group supports the assumption of faecal contamination in drinking water based on the TTC result alone. However, further confirmation of TTC isolates as E.coli proves the presence of faecal contamination. E.coli has the general characteristics of TTCs but, in addition, synthesises the enzyme β-glucuronidase, which has been used as a target for the development of simple, relatively rapid, specific and sensitive detection methods (Tallon et al, 2005). To date, these methods based on specific enzyme detection have not been used widely in developing countries due to the cost of equipment and the availability of reagents. But recent developments have created low-cost packaging for the test that removes the need for equipment (for example see: [http://www.aquagenx.com/](http://www.aquagenx.com/)) and makes it more appropriate for use in low-income settings.

**Enterococci**

Faecal streptococci (sometimes referred to as enterococci or faecal enterococci) are not used as widely as the coliform group in SSA as an indicator of faecal contamination. Of the studies listed in Table 7.1, eight report the use of enterococci.

Enterococci are between ten-fold and a thousand-fold less numerous in human faeces than E.coli, (Gleeson and Gray, 1997; Stevens et al., 2003) but are generally more numerous than E.coli in...
faeces from herbivores. Enterococci survive longer in water than E.coli and can be used to indicate older contamination sources. Furthermore, there is no evidence to suggest that enterococci can replicate in the environment, even in tropical regions where some authors have reported the growth of E.coli.

Several major studies have been done during the last 30 years to determine the relative significance of E.coli and enterococci as an indicator of health risk, rather than as an indicator of faecal contamination. The majority of these studies have concentrated on the health effects of sea-bathing and have reached the conclusion that enterococci are a better predictor of the risk of ill-health than E.coli (for example Kay et al., 1994[90]) and they have now been introduced as the indicator of choice in several countries. The relative significance of E.coli and enterococci as an indicator of health risk in drinking water is less well established; however, Howard et al (2003)[36] conclude from a study of springs in Kampala, Uganda, that faecal streptococci may be more useful as an indicator relevant to public health.

**Impacts from pit latrines**

In-situ sanitation, largely in the form of pit latrines, is the dominant cause of microbiological contamination and a major cause of nutrient loading to water resources in SSA. This is a very well-studied area and a worldwide review has been published recently by Graham and Polizzotto (2013)[91]. The main findings from studies carried out in SSA have been collated in Table 7.2 and are summarised below along with other studies specifically targeting contamination from pit latrines.

**Microbiological contaminants**

Human faeces harbour a large number of microbes, including bacteria, archaea, microbial eukarya, viruses, protozoa, and helminths (Graham and Polizzotto, 2013[91]). In the context of this review there have been no studies that have assessed protozoa or helminths, which exhibit little movement in groundwater due to their size (Lewis et al., 1982[92]). The characteristics of microorganisms and the aquifer and soil environment that affect microbial transport and attenuation in groundwater are shown in Table 7.4.

Microorganisms have been assumed to be rapidly attenuated after excretion but recent studies with viruses suggest that water quality may be impaired for a considerable length of time. Using a mixture of routine culture methods and genetic detection methods, Charles and coworkers detected viruses over 300 days after they were introduced in simulated groundwater systems (Kay et al., 1994[90]). A number of approaches have been used to define the quantities and transport distances of latrine-derived microbial contaminants. The majority of these have been culture-based studies of faecal bacteria; there has only been one study of viruses related to pit latrines (Verheyen et al., 2009[55]).

Attenuation of microbes is likely to be dependent on the hydrological conditions both in terms of water levels and recharge rate and permeability of the aquifer, and is highly variable (see Microbiological indicators of groundwater quality degradation). Dzwairo et al. (2006)[46] found faecal and total coliforms greatly reduced beyond 5 m from pit latrines in Zimbabwe, whereas Still and Nash (2002)[52] found faecal coliforms to be attenuated to <10 cfu/100 mL after 1 metre in Maputaland, KwaZulu-Natal. In Abeokuta, Nigeria, Sangodoyin (1993) found coliform attenuation to be correlated both with distance from the source and with the depth of the groundwater well. In Epworth, Zimbabwe, groundwater contamination was higher in the dry season rather than in the wet, with coliforms detected up to 20 metres from the pit (Chidavaenzi et al., 1997[93]). In Benin, Verheyen et al. (2009)[55] found a positive association for detection of viruses in water sources with at
least one latrine within a 50 m radius. They postulated that during the wet season viruses were transported in shallow groundwater whereas in the dry season contamination was likely to be from surface water.

In an informal settlement in Zimbabwe, Zingoni et al. (2005)\(^{[47]}\) found detectable total and faecal coliforms in over 2/3 of domestic boreholes and wells. In the area 75% of households used pit latrines and there were also informal trading areas. In Langas, Kenya, Kimani-Murage and Ngindu (2007)\(^{[48]}\) found that 50% of wells were within 30 m of a pit latrine and that all shallow wells were positive for total coliforms with 70% >1100 mpn/100 mL; however, in Kisumu Wright and co-workers failed to find a significant correlation between the levels of thermotolerant coliforms in water sampled from shallow wells and the density of pit latrines (Wright et al., 2012\(^{[57]}\)).

### Table 7.4 Factors affecting transport and attenuation of micro-organisms in groundwater (from Mesquita et al., 2013\(^{[83]}\)).

<table>
<thead>
<tr>
<th>Characteristics of the microorganism</th>
<th>Aquifer/soil (environment) properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>Groundwater flow velocity</td>
</tr>
<tr>
<td>Shape</td>
<td>Dispersion</td>
</tr>
<tr>
<td>Density</td>
<td>Pore size (intergranular or fracture)</td>
</tr>
<tr>
<td>Inactivation rate (die-off)</td>
<td>Kinematic/effective porosity</td>
</tr>
<tr>
<td>(Ir)reversible adsorption</td>
<td>Organic carbon content</td>
</tr>
<tr>
<td>Physical filtration</td>
<td>Temperature</td>
</tr>
<tr>
<td></td>
<td>Chemical properties of groundwater (pH etc.)</td>
</tr>
<tr>
<td></td>
<td>Mineral composition of aquifer/soil material</td>
</tr>
<tr>
<td></td>
<td>Predatory microflora</td>
</tr>
<tr>
<td></td>
<td>Moisture content</td>
</tr>
<tr>
<td></td>
<td>Pressure</td>
</tr>
</tbody>
</table>

**Chemical contaminants**

The chemicals of greatest concern from excreta disposed in on-site sanitation systems are regarded to be nitrate, phosphate and chloride. Pin-pointing specific sources is challenging as nitrate may be derived from numerous sources including plant debris, animal manure, solid waste and fertilisers. A common approach has been to compare areas that are similar but have different latrine densities. In an informal settlement in Zimbabwe, Zingoni et al. (2005)\(^{[47]}\) demonstrated that the highest nitrate concentrations were associated with the highest population and pit latrine density. A similar pattern was observed in Senegal and South Africa. (Tandia et al., 1999\(^{[50]}\); Vinger et al., 2012\(^{[51]}\)). Studies in the peri-urban areas of Kisumu, Kenya have shown that the density of latrines within a 100 m radius of the sources was significantly correlated with nitrate levels (Wright et al., 2012\(^{[57]}\)). In eastern Botswana the build-up of nitrogenous latrine effluent in soils and downwards leaching resulted in nitrate concentrations of above 500 mg/L (Lewis et al., 1980\(^{[54]}\)). The highest concentrations are found downstream of areas with high latrine use (Vinger et al., 2012\(^{[51]}\)). Direct measurements are sparse but Graham and Polizzotto (2013) estimate lateral travel distances of 1–25 m for pit-latrine derived nitrate. Sangodoyin (1993)\(^{[94]}\) found that nitrate concentrations were not related to distance from the source in Abeokuta, Nigeria.

Chloride is typically transported with minimal retention and frequently tracks nitrate (e.g. Lewis et al., 1980\(^{[54]}\)) unless subsurface conditions promote denitrification. Ammonium does not tend to accumulate in groundwater near latrines but can accumulate and persist in anaerobic conditions and
when the water table intersects the base of the latrine pit (Ahmed et al., 2002; Dzwairo et al., 2006). Other contaminants include potassium, sulphate and DOC.

**Impacts from non-sanitary sources**

Table 7.3 summarises studies focused on the impact of waste dump sites, industrial activity and mining on groundwater quality. There are only a handful of case studies which have characterised the impacts of waste dumps and industry in urban areas and these are dominated by examples from Nigeria. Examples of contamination from historical mining activity come from Nigeria (Ezekwe et al., 2012) and Zambia (Nachiyunde, Kabunga et al., 2013).

Oyeku and Eludoyin (2010) investigated contamination in wells and boreholes from industrial and waste dumps in Ojota, Nigeria. Sites within a 2 km radius were found to be affected with elevated concentrations of Fe, Cu, Pb and Zn as well as high SEC. In Akure, Nigeria, boreholes in the vicinity of a landfill were found to be contaminated, with high nitrate (36–61 mg/L), Pb and Zn (Akinbile and Yusoff, 2011). In Lagos, Longe and Balogun (2009) found elevated concentrations of nitrate (mean 38.5 mg/L), phosphate (mean 10.7 mg/L) and ammonium (mean 0.2 mg/L) as well as high TDS (3–23 g/L) in wells between 10–400 m from a municipal landfill. Kassenga and Mbuligwe (2009) characterised seasonal and up/down gradient water quality in wells in the vicinity of a solid waste dump in Dar-es-Salam, Tanzania. Higher FC counts were found in sites down gradient (3.4–3.7×10⁴) compared to up gradient (1.5–0.7×10⁴). Higher FC counts were also found during the wet season compared to dry season down gradient of the dump site. Lower SEC as well as SO₄ and Fe were found up gradient and in the wet season, implying dilution from rainfall and recharge and contamination from the dump site.

Elevated concentrations of Pb (0.24 mg/L), Cd (0.25 mg/L) and Zn (1.07 mg/L) were found in wells in the vicinity of mining activities in Nigeria (Ezekwe et al., 2012). A study by Nachiyunde, Kabunga et al. (2013) included sites from the Copperbelt in Zambia and found overall low contamination levels in groundwater with no trace elements above WHO drinking water guideline values. Von der Heyden and New (2004) also carried out a detailed study in the Zambian Copperbelt of the impact of mine tailings on groundwater quality. They found that there was only local effect from the tailings and that concentrations of Co, Ni and Zn were below WHO drinking water quality standards.

**Seasonal trends in groundwater quality**

There are relatively few studies that have undertaken regular water quality monitoring or have carried out seasonal comparisons. A study by Howard et al. (2003) is one notable example where detailed seasonal monitoring of microbiological indicators was carried out over a twelve month period to characterise the risks factors for spring contamination in Kampala, Uganda. Significantly higher contamination was observed after rainfall events and there was strong evidence that rapid recharge of the shallow groundwater causes a rapid response in spring quality (Ishii and Sadowsky, 2008).

Median and maximum results for FS, SEC and NO₃ from four studies that assessed seasonal effects by carrying out sampling at the same sites in both the wet and the dry season are summarised in Figure 7.2. Higher maximum FS counts are found in the wet season compared to the dry season for studies in Uganda (Kulabako et al., 2007) and Malawi (Palamuleni, 2002). Higher maximum SEC are observed in all three case studies in Figure 7.2 during the wet season, however median values are comparable. Changes in nitrate show a mixed picture with higher maximum concentrations in two studies from Uganda and DRC (Kulabako et al., 2007; Vala et al., 2011) during the wet
season, while in the case study from Zimbabwe (Mangore and Taigbenu, 2004) lower maximum values are found. Median values for nitrate are lower in the wet season for both the Uganda and Zimbabwe case studies, which may indicate a dilution effect, while the higher maximum concentrations may be explained as a result of a pulse of contaminants at the start of the rainy season and or evaporative effects during the dry season.

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Figure 7.2 Comparison of groundwater quality during contrasting rainfall regimes. X-axis: a=cfu/100mL, b= μS.cm⁻¹, c= mg/L. Key: 1 = Kulabako et al. (2007), 2 = Palamuleni (2002); 3 = Mangore and Taigbenu (2004) and 4 = Vala et al. (2011). Some data for median and maximum values are not available from the literature.

Understanding seasonal trends in nitrate are complicated by the changes in redox conditions, particularly in low lying areas which are prone to flooding in the wet season which are not uncommon in SSA, e.g. Lusaka, Zambia. These may shift from an oxidising regime in during low water levels which retains NO₃ to a reducing regime where denitrification can take place during inundation (Sanchez-Perez and Tremolieres, 2003; Spalding and Exner, 1993).

Comparisons between difference water sources

The results from Table 7.1 show water quality data from a range of different sources. Open and unlined wells are consistently of poorer quality compared to lined or ‘improved’ wells (e.g. Godfrey et al 2005; Sorensen et al., 2015a; 2015b). In some studies springs have been found to be better quality compared to boreholes (e.g. Takem et al. 2010) and others cases the trend is reversed (e.g. Palamuleni 2002) or both sources were found to have comparable levels of contamination by FC (e.g. Abiye 2008). It is important to note that many of these studies contained very few observations for each source type and generalisations should be treated with caution. However, together they form a more compelling body of evidence.

There is some evidence that the water quality of wells may be affected by usage rates, i.e. with fewer groundwater sources being relied on towards the end of the dry season there is greater risk of contamination, e.g. from materials used for drawing water, especially for unimproved sources (Godfrey et al. 2006). For boreholes this contamination pathway is generally not a major risk factor and this supports the generally better quality found in these types of sources. The lower storage volume of shallow boreholes compared to wells may also be an important factor as this type of contamination can be more rapidly flushed out.

Improved wells do not generally exhibit the same level of gross contamination observed in traditional wells and springs. However, in the majority of studies, wells (both improved and unimproved), are found to have water with unacceptable levels of contamination with faecal coliforms by WHO standards (and typically >100 cfu/100 mL) in at least some part of the year and
often throughout the year. With perhaps the exception of highly karstic settings for microbiological and nitrate the following order of water source quality (best to worst) was found as follows: boreholes >> improved wells = springs > traditional wells.

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