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Internet of Things for Water Sustainability

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Chapter 4
Internet of Things for Water Sustainability

Abstract The water is a finite resource. The issue of sustainable withdrawal of freshwater is a vital concern being faced by the community. There is a strong connection between the energy, food, and water which is referred to as water-food-energy nexus. The agriculture industry and municipalities are struggling to meet the demand of water supply. This situation is particularly exacerbated in the developing countries. The projected increase in world population requires more fresh water resources. New technologies are being developed to reduce water usage in the field of agriculture (e.g., sensor guided autonomous irrigation management systems). Agricultural water withdrawal is also impacting ground and surface water resources. Although the importance of reduction in water usage cannot be overemphasized, major efforts for sustainable water are directed towards the novel technology development for cleaning and recycling. Moreover, currently, energy technologies require abundant water for energy production. Therefore, energy sustainability is inextricably linked to water sustainability. The water sustainability IoT has a strong potential to solve many challenges in water-food-energy nexus. In this chapter, the architecture of IoT for water sustainability is presented. An in-depth coverage of sensing and communication technologies and water systems is also provided.

4.1 Introduction

When the well runs dry we know the worth of water.—Benjamin Franklin

The survival of the humanity is contingent upon the availability of water. The aquatic ecosystems that include groundwater, oceans, river, lakes, streams, and estuaries supply a wide range of resources and services to the community [18, 56]. These are importantfor water storage, regulation of water quality and quantity, food provision, recreation, and transportof water and substances to downstream [14, 92]. The droughts and flooding impacts the normal functionality and is a main cause of reduction in its tolerance and diversity, a vital factor for sustainable community [63, 126, 131]. The contents of the chapter are shown in Fig. 4.1.

Fig. 4.1 The internet of things for sustainable water

The water, energy, and land-based systems are linked in many different ways [39, 63, 107]. The precipitation patterns are changing rapidly due to the ocean and atmosphere warming [14, 17, 31, 33, 43, 101]. The most visible effects of these phenomena include increase in the duration of dry periods, higher evaporation, and rapid snow melt [46]. These cascading effects propagate to the water cycle, which encompasses complete and dynamic processes of water movement and circulation in the Earth system. Due to global warming effects, these water cycle processes (see Fig. 4.2) are exhibiting unpredictable increase and decrease with abundant (flooding) or little to no water availability (drought) [33]. The decrease in the amount of available water is a major threat to entire ecosystem. Similarly, flooding poses a major risk to communities and infrastructure.

Significant changes are also being observed in streamflow patterns with peak flows moving to the beginning of the year [111, 133]. The increase in amount of rain as compared to the snow is also impacting water storage facilities. The rate of evapotranspiration is a major element of the water cycle, which represents the evaporation of water from different sources such as oceans, lakes, plants, soils, and rivers [93]. Its rate is impacted by wind, solar radiation, humidity, and wind. Consequently, water content of soil, water runoff, and groundwater recharge are impacted by these variations in rate of evapotranspiration [33, 78]. Among these factors, the soil water content is significant because of its implications in agriculture and air evaporation and temperature. This increase in evaporation is considered to be a big factor contributing to increases in dry periods and shorter droughts on seasonal basis [42]. These changes in precipitation patterns are also impacting the municipal water supplies [103]. For a reliable water supply to cities, the utility management companies are facing many challenges in water storage

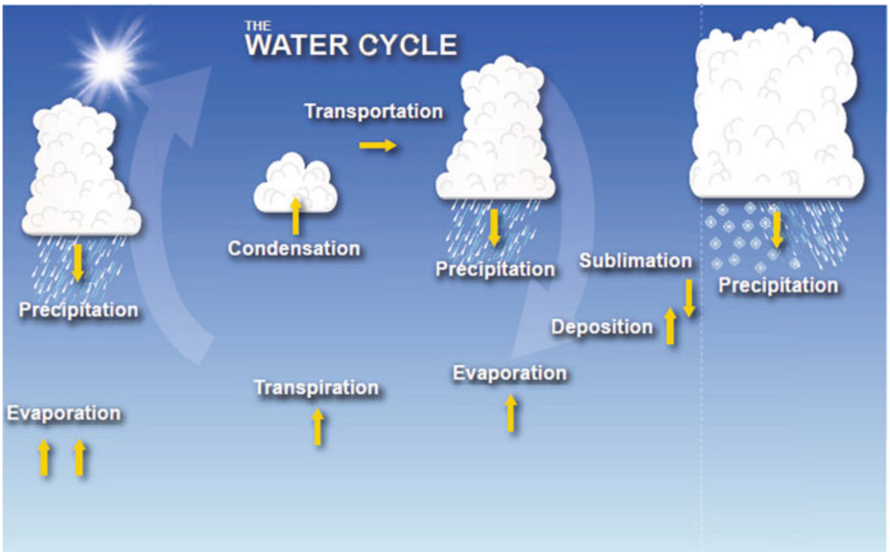

Fig. 4.2 The water cycle

due to projected decline in supply and increasing population. World population is expected to reach 9.8 billion people by 2050, with corresponding increase of a 25 to 70% in food production [129]. The world food production challenges span beyond UN agenda of eradicating malnutrition and poverty by 2030. According to WHO, daily minimal human demand of water is 1.84 gallons per day, whereas the recommended water need to maintain adequate hygienic is 5.28 gallons [109]. For a total human population of 7.7 billion, the global water need of freshwater is 40.65 billion gallons. UN sustainable development goal (SDG 6) is about providing safe water [110].

The crop and landscape irrigation also depends on the water, being the largest withdrawal of water. Although 3/4 of our planet is covered with water, only 2.5% constitutes the freshwater. Approximately 70% of the available freshwater is frozen in glaziers and the ice caps. The residual 0.75% of freshwater is in swamps, subsurface, lake and river, living organisms, and the atmosphere. The 70% of the remaining 0.75% of freshwater is utilized in irrigation.

Water quality is another major challenge. The high streamflow takes sediments and pollutants to the water. Whereas, the well below-average rates of streamflow also result in decrease of water quality. Similarly, heavy precipitation, increased intensity and scale of wildfires, impacts fertilizer usage contributes nutrients, contaminants, and sediments from the surface water to downstream [35].

The freshwater aquifers and wetlands are also vital for the water sustainability. These are being undermined by many factors including changing sea levels, surface and groundwater usage, and storm surges [16]. The saltwater gets mixed with underground and surface water due to rise in sea levels. The saltwater also flows upstream to make up the deficiency in river flows that is caused by high withdrawals. Moreover, storm surge and rise in sea levels also impact the urban underground infrastructures such as storm drainage and sewer treatment.

In water-energy nexus, the demand of water for energy production is increasing rapidly. Water is needed in hydro-electric dams for turbine, in thermo-electric power plant for steam, and cooling of the equipment in nuclear power generation to absorb heat. Likewise, the energy is needed to draw out water from rivers and aquifers, to transport it to storage and treatment facilities, to distribute water supply, and finally, to collect waste water. Collectively, energy and water need land resources.

4.2 Water Sustainability IoT

The water sustainability IoT contain components such as water things, sensing, water quality measurements, cleaning and treatment technologies, and water resource management. The elements of the water IoT are shown below:

- Groundwater, fresh water, and surface water
- Precipitation, river flow, lakes, and wetlands
- Evapotranspiration, hydrology, and hydraulics
- Aquifer and runoff
- Irrigation, recycling, and cleaning

4.3 IoT as an Enabler for Sustainable Water

In this section, the IoT paradigm is discussed as an enabler of sustainable water.

4.3.1 Advantages of Sustainable Water IoT

The water IoT is envisioned to provide accurate decision support systems to guide technological and societal progress in water use. It enables annual precipitation monitoring and river-flow variation observations. Accordingly, very heavy precipitation, dry periods, and seasonal and short- and long-term droughts can be predicted at spatial and temporal scale. Moreover, based on the IoT sensing technologies for withdrawal of groundwater, and aquifer recharge, the availability of demand can be ascertained. The surface and groundwater supplies are decreasing because of the consumption, withdrawal, precipitation, runoff, combined with changes in consumption and withdrawal. The determination of variations in surface water and groundwater usage patterns will help to attain substantial freshwater aquifers and wetlands. The total precipitation measurements can be used to forecast potential flooding threats. Therefore, risks to economy, community infrastructure, human health and property, and human safety can be reduced.

The state-of-the-art IoT technology, ecological standards, and indicators are useful in achieving sustainability goals. There are many advantages of the water IoT for sustainable community development. The cumulative water withdrawals scale and impact can be modeled on ecosystem through IoT data collection tools. The development of novel sensing technologies enables monitoring of water IoT such as wetlands and lake inflows. Accordingly, based on the sensing of water IoT, better approaches can be developed for water sustainability indicators which will contribute to the aquatic and terrestrial ecosystem resilience. Other important enabling sensing includes water and air temperatures, runoff, and precipitation.

Using the integrated water IoT paradigm, the connection between ecological parameters and hydrology flow regime and groundwater can be better understood through the identification of impact of flow regime thresholds. One example is flow variations link to invasive species. The water quality can be improved by reduction of pollutants caused by human activities. The IoT paradigm can also inform deployment of new systems for reduce water use. Moreover, the water cleaning and recycling technologies can be developed and integrated into the system through sensing of the water pollutants, nitrogen, and sediments. Accordingly, lake and water quality can be improved. Moreover, critical data sets (e.g., data related to stream and river flow, groundwater, waterborne disease, water usage, and paleoclimate reconstruction) can enable advance research and better understand of the echosystem (Fig. 4.3).

4.3.2 Research Challenges Needs in Sustainable Water IoT

In this section, the research needs in support of all aspects of the sustainable water ecosystem are discussed.

- The better insights are needed in relationship between groundwater and surface water through improvements in water IoT monitoring tools and infrastructures [34, 48].
- In the ecology domain, a particular emphasis is needed on sensing of ecological parameters and lakes, wetlands inflows. The connection between point and non-point sources against freshwater supply also needs more investigation [45].
- In urban localities, more advanced real-time pathogens, contaminants and chemical compound sensing technologies are needed. Novel techniques are needed for nutrient reduction, detection of new type of contaminants, spill detection, source tracking [60].
- There is need of whole cycle measurements integration into sustainable water IoT with emphasis on communication networks to eliminate dependency on detached measurements to assess the effects of climate change, land use, water conservation activities including water source and discharge [44].

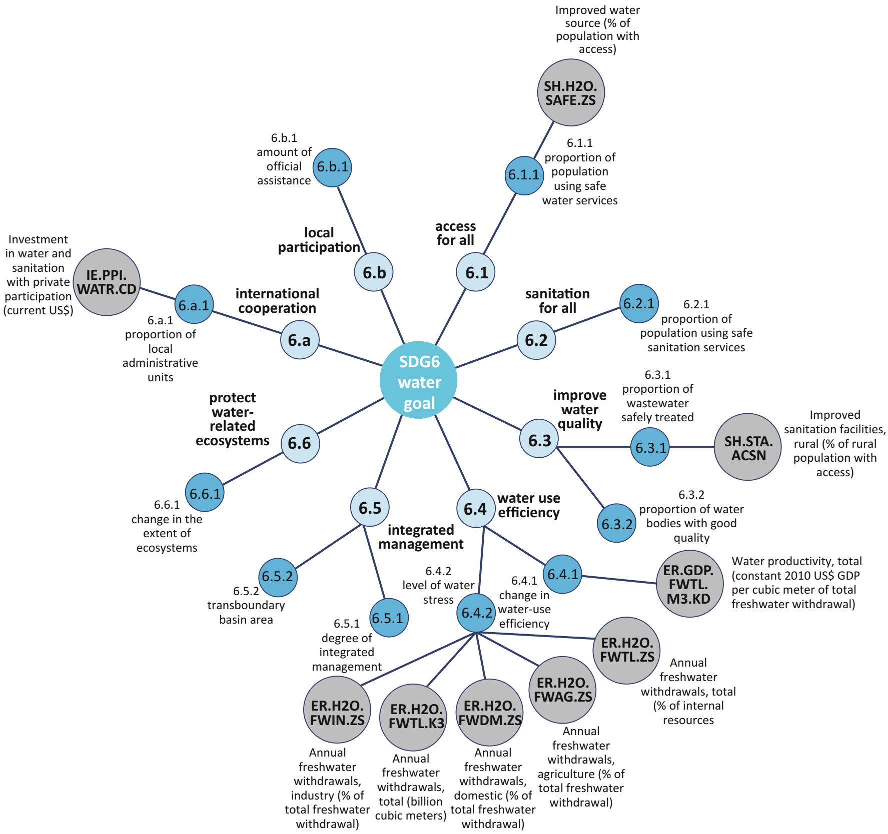

Fig. 4.3 The sustainable development goals related to water sustainability

- Other important technology needs for sustainable water integration are in the area of inexpensive storage and metal removal [22, 127].

4.4 Water Sustainability IoT Monitoring and Applications

The water quality is indicator of the state of biological, chemical, and physical properties of water [115, 123]. The importance of the water quality for sustainable environment and ecosystem cannot be overemphasized [130]. The water quality measurements in river and lakes and other water bodies are important to identify inadequate oxygen supply caused by extra amounts of nutrients and algal blooms. Through monitoring the impact of the climate change, human activities can be better understood [57]. Accordingly, it enables better decision and policy making. Moreover, the impact of the sediment loading can also be analyzed by using the turbidity measurement. The monitoring can be done by using different approaches such as sampling, continual monitoring, and remote sensing are all used to collect water quality data in estuarine and coastal ecosystems, surface and ground water, stormwater, and ballast water [57]. In this regard, novel pathogens, nutrients, and chemical contaminants sensing technology are needed.

Similarly, the water monitoring in urban areas includes:

- Accession and transport of rainfall and runoff data for sewage and stormwater networks [105]
- Management of stormwater retention base [122]
- Water supply infrastructure monitoring [95]
- Pipeline system to identify issues related to water supply shortage [54]
- Industrial activities impacted water quality monitoring [69]

For sustainable water IoT, development of novel monitoring technologies for the entire water cycle is needed. The sustainable water IoT is envisaged as to integrate different type measurements at large scale. This paradigm removes the issue of single point failures and insufficient data for decision making. It also gives insights into the baseline conditions at different spatial and temporal scales (including natural perturbations and industrial impacts). Accordingly, various relevant baseline indicators can be utilized for policy making and remedial actions by providing accurate and certain data. The sustainable water IoT enables development and integration of different types of systems for robust evaluation of water ecosystems. The predictive models can be developed and integrated into the paradigm for different water use scenarios (e.g., drinking water, discharge, and industrial use).

4.4.1 Applications

The important water monitoring applications are discussed below:

- Potable water monitoring. For chemical properties including pH, nitrates, and dissolved oxygen (DO).
- Chemical leakage monitoring. The extreme pH and low dissolved oxygen levels are used to identify spills because of sewage treatment plant or other pipeline issues in rivers.
- Pollution levels monitoring: Temperature, pH, salinity, nitrates dissolved oxygen monitoring in seawater.
- Corrosion and limescale deposit monitoring: The pH, conductivity, Calcium (Ca+) temperature, and magnesium (Mg2+) concentrations monitoring.
- Aquatic life conditions monitoring. Water conditions of aquatic animals such as fish.
- Swimming pool monitoring: The pH, oxidation-reduction potential (ORP), and chloride values to assess water quality in swimming pools.

4.4.2 Source Water Monitoring

Source water is impacted by different factors including seasonal weather changes, and upstream discharge. The source water quality monitoring enables selection of proper treatment options. Groundwater has low content of natural organic matter (NOM) and therefore can be disinfected by using chlorine disinfection techniques.

4.4.2.1 Surface Water

Surface water comes from rivers, lakes, and other reservoirs. It is the vital source of water production. The groundwater has high content of natural organic matter (NOM) and needs proper disinfection techniques.

The important water monitoring parameters are discussed below:

- Ammonia. The ammonia level can change remarkably in all seasons and requires consistent monitoring. Ammonia reaction chlorine disinfection leads to formation of chloramines which produce different issues [51].
- Free Chlorine: The free chlorine is mixed to the groundwater for ammonia transformation to chloramines, which breaks by further chlorine, hence making free chlorine as leftover disinfectant. The free chlorine monitoring is done to achieve desired levels. It is also used to eliminate amalgamation of manganese and iron and manganese for subsequent removal through filtration [85].
- pH. The pH is used for chlorine disinfection process optimization. It indicates the acidity and alkalinity of water [25].
- Total organic carbon. The TOC is measure of the carbon present in organic compounds of the water. It guides selection of proper treatment method through byproduct precursor's removal [79].
- UV254. The UV254 gets its name from its wavelength of 254nm. It is used to measure organic matter (OM) in water. The OM reacts to chlorine to form disinfection byproducts (DBPs). Different events impact the OM in the water such as storm, increase in nutrients from human activities [128].
- Turbidity. The turbidity is the indicator of water transparency loss caused by the suspended particulates. The large turbidity levels negatively impact the disinfection process by preventing the ultraviolet disinfection. Turbidity variations also indicate weather events such as rain and floods [96].

4.5 Sensing in Sustainable Water IoT

The real-time sensing is a vital component of the sustainable water IoT. The monitoring applications enabled through this sensing mechanism are being adopted by industry. It also enables improved efficiency water treatment and recycling operation. A detailed overview of water sensing technologies is given in next section.

4.5.1 pH Sensing

A common measurement of the water is pH, which is equivalent to negative of the logarithm of hydrogen-ion concentration in water. It is used to measure acid and alkaline properties of water on a scale of 0–14, where 7 is considered as neutral. The pH value higher than 7 denotes alkalinity, whereas the values less than 7 indicate acidity. An increase or decrease of 1 in acidity or alkalinity represents ten times change. Different types of the pH sensors are explained below:

4.5.1.1 Combination (Electrochemical) pH Sensor

The combination(electrochemical) sensor is a widely used method to sense pH values [10]. It consists of a reference and measuring electrodes. Where the actual detection of the pH variations is done based on the measurement electrode and reference electrode provides a steady signal for comparison purpose. An impedance based metering instrument is used for pH value visualization which converts millivolt signal to pH values.

4.5.1.2 Three-Electrode pH Sensor

Three-electrode pH sensor also referred to as differential pH use three electrodes for pH measurements [55]. Where the differential detection of the pH variations is done based on the measurement of two electrodes and reference metal ground electrode provides a steady signal for comparison purpose. Three-electrode pH sensor is less error-prone in terms of reference signal.

4.5.1.3 Laboratory pH Sensor

The laboratory pH sensor is a type of electrochemical pH installed in 1.2 cm glass/plastic unit. This type of sensor is used in laboratory for learning and discovery purpose. This is also used in environmental monitoring and pool sampling and can be easily tailored to match desired application requirements [82].

4.5.1.4 Single-Chip pH Sensors

The single-chip pH sensors are used for pipeline and underground tank monitoring. It is designed to provide continuous monitoring of the pH values. Its robust design can sustain harsh environment with capability to work for longer duration for duration without interruption [41].

4.5.2 Conductivity Sensing

The electrical conductivity, reciprocal of resistivity, is the measure of the capability of a solution or medium's electric conductance [80]. Without the presence of ions, the water is not a high conducting medium. Therefore, conductivity measure indicates the amount of ion present in water. The electrical conductivity measurements can be presented in different units (e.g., ion concentration TDS, and salinity). It is expressed in micro-Siemens per centimeter, μS/cm, micro-Siemen. For higher conductivity values are also expressed in milli-Siemens. There are several different conductivity measurement units in use today.

4.5.2.1 Conductivity Measurement Units

Conductivity measurements are often converted into TDS units, salinity units, or concentrations. These units of measurements are explained in the following:

- Total dissolved solids. TDS is the indirect measure of number of ion amount, measures through electrical conductivity, that is indicated as parts per million (ppm) or mg/l [94]. In environment, where highly dissolved ionic solids are present, the TDS measurements produce accurate results. The TDS is also being used in water treatment industry.
- Salinity. It is also an indirect measure which is usually expressed as ppt. Both TDS and salinity measurements are sensitive to temperature, ion types, and concentration. Accordingly, one unit can be converted to another [84].
- Concentration. Based on the knowledge of the composition of the ions, the concentration can be ascertained from the conductivity [8].

4.5.2.2 Conductivity Sensors

The electrical conductivity sensors are based on inductive, 2-electrode, 4-electrode based methods. These electrical conductivity measurements from these sensors can be changed to salinity, total dissolved solids, and concentration. Different types of conductivity sensors are discussed in the following:

Contact-Based Conductivity Sensors The contacting conductivity sensors are used to conductivity by making a physical contact, from two sides, to the understudy material [90]. These sensor sides are made by using different materials such as platinum, graphite, steel. An alternate current (AC) waveform is applied and transmitted through once, which then propagates through sample being sensed. Accordingly, the signal is received at the other side where its intensity is used to measure the conductivity in TDS, or micro/milli-Siemens.

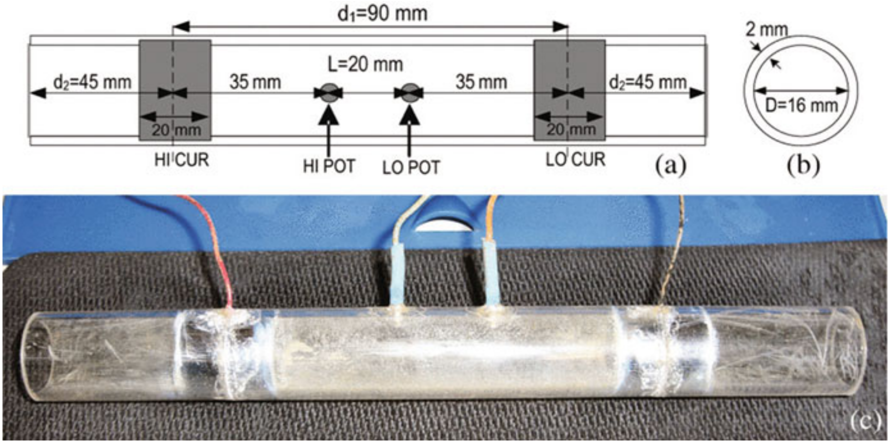

Fig. 4.4 A four-electrode conductivity sensor and an integrated temperature sensor unit. (**a**) Longitudinal sectional-view geometry. (**b**) Transversal sectional-view geometry. (**c**) Actual sensing unit [90]

Inductive Conductivity Sensors The inductive conductivity sensors, also called the toroidal conductivity sensors, work on the principal of magnetic induction by use a two coil (antenna) induction system in plastic assembly. The transmitter antenna induces a magnetic field that produces an electrical current on the understudy sample. The receiver antenna measures the magnetic field, where the corresponding current intensity indicates the ion concentration. Due to its ability to remove polarizing effects and fouling resistant, the inductive sensor produces high quality measurements as compared to the contact-based conductivity sensor. The toroidal sensors are being used in sea water monitoring. A four-electrode conductivity sensor and an integrated temperature sensor unit are shown in Fig. 4.4.

Conductivity in Water Treatment Based on the application need, various levels of conductivity values are used to assess the purity of the water (e.g., drinking water generally has the conductivity value of around 1 milli-Siemens per centimeter, highly pure water has the conductivity values are less than 1 micro-Siemens per second).

The conductivity levels of the different liquids are given in Table 4.1 [100].

4.5.3 Dissolved Oxygen Sensing

The oxygen dissolved per unit of water is called dissolved oxygen (DO) [83]. Water gets oxygen through different ways:

- The aeration also known as movement by turbulence
- Through diffusion in surrounding air

Table 4.1 The conductivity levels of the different liquids

Liquid type	Conductivity level
Fresh water	0–1 mS/cm
Ultra-pure water	0.00005 mS/cm
De-ionized water	0.00005–0.001 mS/cm
Reverse osmosis water	0.00005–0.2 mS/cm
Drinking water	0.20–0.80 mS/cm
Slightly salty water	1–45 mS/cm
Sea water	45–73 mS/cm
Highly salted water	72+ mS/cm

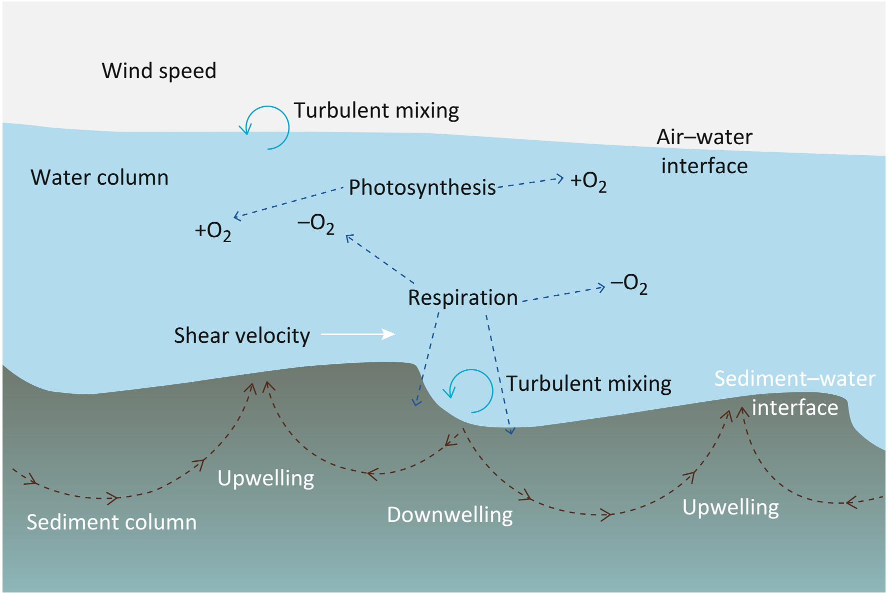

Fig. 4.5 A schematic side view showing major processes controlling stream and benthic dissolved oxygen concentrations [9]

- Aquatic plants
- Plant waste by photosynthesis in water column
- Atmosphere

Still water sources (e.g., lakes) have low oxygen as compared to the running water source such as streams and rivers. A schematic side view showing major processes controlling stream and benthic dissolved oxygen concentrations is shown in Fig. 4.5. The DO is a vital indicator of the quality of the water and aquatic life as oxygen is must for breathing. Different types of DO sensors are explained in the following.

4.5.3.1 Galvanic DO Sensor

The galvanic DO sensors use a cathode and anode with an oxygen permeable membrane to separate these two from the sample understudy water [9, 37]. The purpose of the permeable membrane is to permit oxygen contained in the sample to be diffused in the instrument, accordingly, the cathode reduces it there. Due to this chemical reaction, an electronic signal is generated that propagates from cathode to anode, and subsequently into the sensor, where the difference in pressure is measured that changes according to the samples oxygen's pressure. Because the diffusion rate and partial pressure increase with oxygen concentration, there is a proportionalincrease to the current.

4.5.3.2 Optical Dissolved Oxygen Sensors

A die is used in the optical dissolved oxygen sensor [66] to sense wavelength of the light. Then a paint layer of oxygen is placed on the dye which molecules interact with iluminescence. It acts as a filter for other compounds. The color of the die changes to glowing red when it is exposed to the light. The sensor measures luminescence from the emitted light by using the photo-diode, which is compared to reference value to ascertain oxygen dissolved in water.

4.5.4 Eutrophication and Nutrient Sensing

Eutrophication is unrestrained intake and enrichment of nutrients (e.g., nitrogen and phosphorus) which mostly come from anthropogenic sources (e.g., human activities) [53, 116]. This issue is being observed in reservoirs, rivers, estuaries, lakes, and other coastal regions. The presence of high nutrients concentrations leads to productionof toxins, hypoxia, fish kills, and harmful algal blooms (HABx) that are harmful to aquatic life and humanity [11, 13, 36, 71]. These nutrients are carried along with agricultural runoff, domestic yard fertilizers and detergents, fossil fuels combustion caused atmospheric deposition, stormwater, wastewater. Due to infeasibility of mitigation, preventing that high intake in lakes, rivers, and oceans through nutrient sensing and in situ measurements is a viable option to avoid potential problems to the ecosystem. Accordingly, compliance limits for nutrient discharges can be established. The nutrient sensing also enables other policy level decisions such as flow rate and treatment options at water bodies. It also provides insights into the relationship of geochemical, hydrological, and biological processes. With the increasing severity and intensity of HABs, there is a need of in situ nutrient sensors for nitrate, ammonium, nitrite, ammonia, total phosphorus, total nitrogen and soluble reactive phosphorus with strong emphasis on the nitrate and nitrite sensors. The nutrients sensing technologies are discussed in the following:

4.5.4.1 Optical Nutrient Sensor

It works by using advanced spectral absorption (UV) [113] through a photometer and provides accurate and high resolution, and chemical-free fast response time. However, it is expensive and only senses nitrate. Moreover, the energy consumption of the sensor is high. It can operate in harsh environments such as blue-ocean nitraclines, storm runoff in lakes and rivers, and streams [72].

4.5.4.2 Wet-Chemical Sensor

It operates on the principal of wet-chemical calorimetric reaction with sensing through photometry [6]. It also provides accurate high resolution measurements of phosphate, ammonium, and nitrate. It is suitable for point and non-point source nutrient measurements in different environments (e.g., lakes, reservoirs, rivers, streams, rivers, canals, and channels, estuaries, and oceans) It supports real-time measurement of dissolved phosphate.

4.5.4.3 Ion-Selective Electrodes Sensor

It operates on direct potentiometry between a reference electrode and a detecting electrode [24]. It can sense ammonium and nitrate. However, it has low resolution as compared to the wet-chemical sensors and optical sensor. The accuracy of this sensor is also sensitive to the ionic interference.

4.5.5 Water Flow Sensors

The water flow and discharge measurements are important to ascertain the water amount flowing through a channel. These sensors are also used to predict flooding. In flow rate measurements, different inferential approaches such has change in water velocity and kinetic energy are employed. The different types of water flow sensors are explained in the following [50]:

- Rota-meter. A rotameter is used for volumetric flow rate measurement of fluids in a closed tube. It works by allowing flow to the cross-sectional where the travel of the flow changes and accordingly can be measured [59].
- Magnetic-flow meter. A magnetic flow meter is a flow measurement instrument that works on the voltage induction principal. It measures the flow by using a magnetic field which causes difference in potential corresponding to the velocity of flow normal to flux lines [52].
- Turbine flow meter. A turbine flow meter is used to sense the volume of the flow by using the rotation of the blades caused by the movement of flow. By measuring

the rotor velocity which is directly proportional to the fluid velocity, it provides accurate measurements [3].

- Venturi-tube flow meter. Venturi meter is used to measure flow by using a pipe's converging section to induce an increase in velocity of low, which leads to a proportional drop in pressure that is used to deduce flow rate can be deduced. The water supply industry uses Venturi-tube flow meter for flow measurements [62].

4.5.6 Temperature Sensing

A temperature sensor, as the name indicates water temperature measurement instrument [114]. The different types of temperature sensors are explained in the following:

- Thermocouple. A thermocouple uses two different types of electrical conductors which are used to form junctions at two different temperatures [67]. A thermocouple generates a voltage that depends on the temperature (thermo-electric effect). Accordingly, the voltage interpretation provides temperature value.
- Resistance Temperature Detector. A RTD determines temperature by using the electrical resistance of the sample under study which changes with the change in temperature [5].
- Thermistor. The electrical resistance of the thermistor changes with temperature and accordingly is used to measure temperature [120].

4.5.7 Satellite Sensing

The water remote sensing is used for recording the water color spectrum (color of water body) and is based on optics and water's apparent optical property [19, 47]. It is used to sense presence of different natural components of the water. When the light field is applied to water, the angular distribution of the field impacts the water color depending on the type and amount of water substances. Therefore, the concentrations of optically active substances are determined with this distribution changes [30].

The reflectance of the light from the water surface is measured using different types of optical measurement device such as radiometers, and spectrometers mounted on air- and space-born devices. The water quality is studied from different parameters such as chlorophyll-a and suspended particulate matter concentration, where high amount of detected concentrations of these parameters show eutrophication-caused algal bloom (HAB).

The Ocean Color Radiometry Virtual Constellation (OCR-VC) is a system to produce data sets by using ocean color radiometry satellites to assess the climate change impacts [38].

The various ocean color radiometry networks are listed in the following:

- International Network for Sensor Inter-comparison and Uncertainty Assessment for Ocean Color Radiometry (INSITU-OCR). The purpose is to integrate and visualize different remote sensing tools for satellite sensor inter-comparisons and uncertainty assessment for remote sensing products
- Ocean Color Essential Climate Variables (ECV) [97]
- Global Climate Observing System (GCOS) [20]
- International Ocean Color Coordinating Group (IOCCG) [136]

4.6 Sustainable Water IoT Technologies and Systems

In this section, the sustainable water IoT technologies and systems are discussed.

4.6.1 Water Pollution Control

The discharge of toxic substances due to human activities (e.g., herbicides, domestic wastes, and insecticides) is one of the main factors contributing to the water pollution [68, 91]. Various types of compounds and chemicals are being detected in water sources indicating the severity of this issue. The other water pollutants come from livestock farms, waste from food processing plants, metals and chemical waste. Due to various types of water pollutants, a range of diverse techniques and methods are being used in water treatment. An architecture of a low-cost sensor network for real-time monitoring and contamination detection in drinking water distribution systems is shown in Fig. 4.6. The surface water and groundwater are two types of drinking water which generally require treatment for following types of contaminants [70, 132]:

- Biological contaminants (e.g., disease-causing bacterium, protozoa phylum, viruses, and parasitic worms [2]
- Inorganic chemicals (e.g., nitrogen species, metals, oxyanions, and radioactive nuclide) [134]
- Organic chemicals (e.g., natural organic matter (NOM) and faux organic chemicals from agro-industrial products) [7]

The major water treatment technologies are [15]:

- Coagulation. The solids are separated through the sedimentation process. It is then followed by the filtration process because the slowly settling tiny particles are hard to remove through the settling. Therefore, coagulation (grouping) is done through chemicals (e.g., alum) to form large particle groups.
- Membrane process. This treatment method is used filter out undesired pollutants from water. A membrane also acts like a filter with a capability to block certain

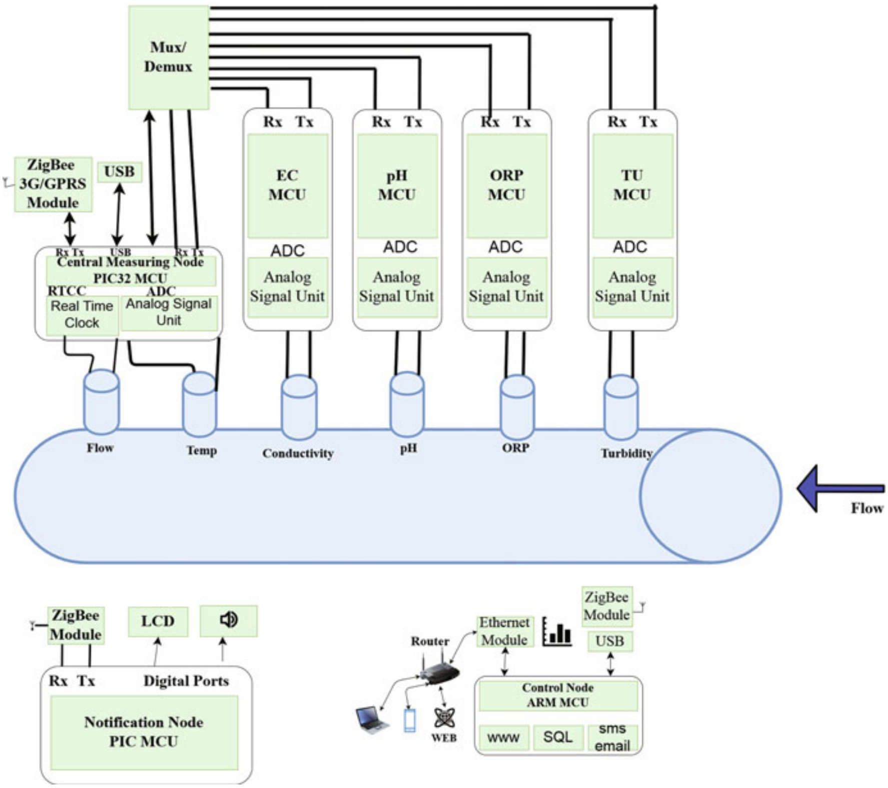

Fig. 4.6 An architecture of a low-cost sensor network for real-time monitoring and contamination detection in drinking water distribution systems [58]

constituents. It is employed in ground and surface water to obtain water for drinking, and to wastewater for industry needs.

- Adsorption and Biosorption. Adsorption refers to surface accumulation different components. It is a gas– or liquid–solid phenomenon. The biosorption process includes ion exchange (arsenic removal), complexation (complex association), surface precipitation, chelating (bonding), and coordination.
- Dialysis. The dialysis water treatment process is used to remove microbial and chemical compounds in two steps: (1) pre-treatment, where compounds are eliminated from the source water to get an early stage clean water, and (2) de-activating the leftover chemical and microbial compounds.
- Foam flotation. In dissolved air flotation (DAF) is a waste water treatment process oil and solids are removed. In this process, the high pressure air is dissolved in the water. Then, at atmospheric pressure, it is released in through flotation. The bubbles carry suspended matter adhered to them which is subsequently removed through skimming.

- Reverse Osmosis. Reverse osmosis (RO) uses the membrane process to filter dissolved compounds and suspended particles from water. Activated carbon (AC) filtration is also used to filter pesticides, chlorine, and organic solvents which are not filtered by RO. The sediment filtration removed silt particles.
- Photo catalytic degradation. It is used for reduction and oxidation of metals, photo catalytic reduction of oxyanion contaminants (e.g., NO_3^-, ClO_4^-), and destruction of per/polyfluoroalkyl substances (PFAS). The semiconducting material is also employed as heterogeneous photocatalyst.
- Biological and Bio-analytical methods. This process is based on the filtration of oxygenated water via different types of granular solids such as sand, coal, and granular activated carbon (GAC).

4.6.2 *Ocean Acidification and* CO_2 *Mitigation*

Ocean acidification (OA) is the process in which the acidity of ocean increases (decrease in pH value below 7) [40]. The UN Conference on Sustainable Development has declared OA as a major challenge to economically and ecologically ecosystem sustainability. The main cause of the ocean acidification is increase in CO_2 concentration from higher emissions which leads to chemical changes in sea water. Local and coastal pollution is also attributed to the ocean acidification. This process is harmful for the marine habitats in the ocean ecosystem. The following two methods are used for OA sensing [28]:

- OA Observing Vessels. In this approach, the sampling is done using research ships to sense variations in seawater carbon related chemical properties. The pH is the main parameter being measures using pH sensors. Moreover, by using this approach ocean acidification mitigation methods can be deployed at a large scales [21].
- Buoys and Autonomous Systems. For continuous and autonomous carbon measurements, the buoys are being used for high frequency measurements to get insights into variability in ocean acidification over diurnal, monthly, and yearly scale. These can be used to measure pH, bio-geo-chemical, and CO_2 in coral reef waters, sea, and coastal areas [99].
- Hydrographic Cruises. This approach is used to obtain for physical, chemical, and biological measurements of full vertical column base in harsh sea environments [23]

Although, OA can be mitigated through by limiting the emissions of atmospheric CO_2 levels, other options include restoration of wetlands, planting new forests and reforestation to increase absorption of atmospheric CO_2 levels, and by adding alkaline minerals to seawaters. Through IoT based decision support system following developments can also help in OA mitigation:

- Sensing of runoff and pollutants from fertilizers
- Digital fisheries management approaches
- Monitoring and protection of sediment loading and development of application of marine spatial monitoring
- Monitoring of local emissions sulfur dioxide and nitrous oxide emissions from coal plants

4.7 The Sustainable Water Case Studies

The case studies are discussed in the following:

4.7.1 Open Water Web

The open water data is an initiative of Advisory Committee on Water Information to integrate scattered water information into an open data web by leveraging prevailing infrastructure, systems for the purpose of development of novel water solutions and models, and for data sharing purpose [4]. The different components of the open data web are shown in Fig. 4.7. The three different use cases of open water web are given below:

- The National Flood Interoperability Experiment (NFIE). The purpose of this experiment to develop next-generation of flood hydrology tools.
- Water Supply Decision Support System. A tool to past and future water interactions in lower Colorado River basin.
- Spill response/Water Quality. To get better insights into the impact of spills on public health.

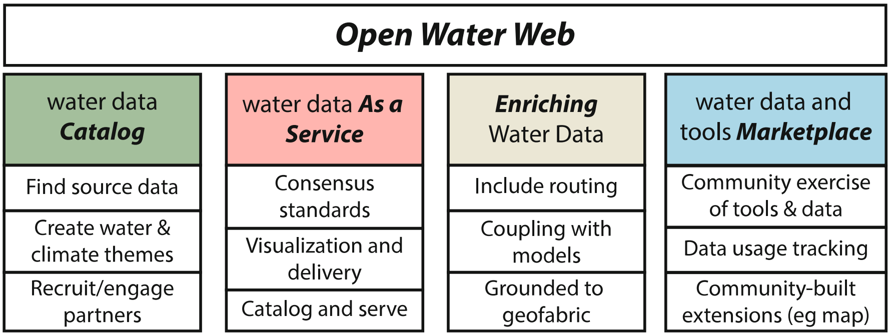

Fig. 4.7 Different components of open water web

4.7.2 Waspmote Smart Water

The Waspmote Smart Water platform contains low energy consumption sensors for real-time sensing in harsh environment for remote water quality monitoring [61]. This platform supports real-time measurements with connection to cloud online data processing. It is used for conductivity, dissolved oxygen, temperature, pH, and transparency loss. It supports following type nutrient and dissolved ions sensing:

- Fluoride (Fluoride (F^-), Nitrate ($NO_3{}^-$), Calcium ($Ca_2{}^+$)
- Chloride (Cl^-), Silver (Ag^+), Cupric (Cu^{2+})
- Potassium (K^+), Iodide (I^-), Fluoroborate ($BF_4{}^-$)
- Ammonia (NH_4), Perchlorate (ClO_4), Magnesium (Mg^{2+}),
- Nitrite ($NO_2{}^-$), Lithium (Li^+), Sodium (Na^+), Bromide (Br^-)

4.7.3 National Network of Reference Watersheds

The National Network of Reference Watersheds (NNRW) is a system of watersheds and monitoring networks with minimal disturbances [75]. These reference (pristine) watersheds are safeguarded from the impacts of human activities and related changes. These reference watersheds are used for empirical measurements of variations in water quality, physical, biological, and chemical properties of soil and vegetation. Accordingly, the data collected by these measurements is compared with data collected from disturbed watersheds to assess impacts.

4.7.4 Hydrometeorology Testbed

The hydrometeorology testbed (HMT) is a testbed at the Weather Prediction Center (WPC) [32, 135]. It is used for enhanced forecasting of extreme precipitation, and forcings, hydrologic prediction, through experiments and advanced hydrometeorological empirical observation. Schematic diagram showing the orientation of the soil probes and surface meteorological observations used at a typical soil moisture observing station is shown in Fig. 4.8. At HMT, two types of experiments are conducted which are discussed in the following.

4.7.4.1 Winter Weather Experiment

In this experiment, the precipitation algorithms are applied to various models during different weather events to observe transition zones of precipitation types. Their use is analyzed as input to manually produced empirical forecasts. The winter weather event ensemble predictability is evaluated using a tool that uses ensemble clustering.

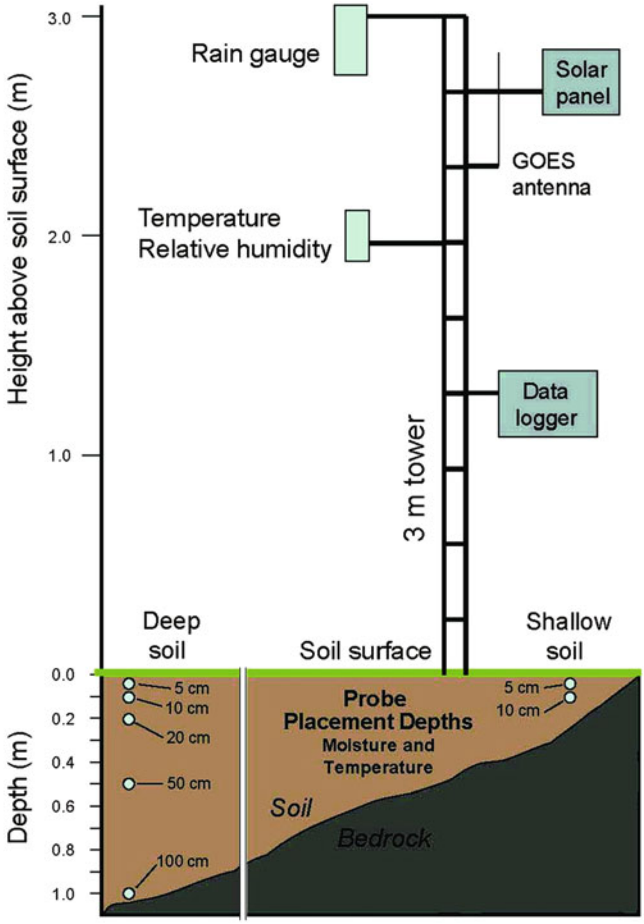

Fig. 4.8 Schematic diagram showing the orientation of the soil probes and surface meteorological observations used at a typical soil moisture observing station [135]

4.7.4.2 Flash Flood and Intense Rainfall Experiment

In this experiment, short-range flash flood forecasts are produced by using high resolution data to synthesize atmospheric and hydrological guidance. This experimental hydrologic guidance includes parameters such as runoff, soil saturation, probabilities of quantitative precipitation forecasts (QPF) exceeding recurrence intervals, and streamflow anomalies.

4.7.5 *WaterWatch*

The WaterWatch is comprehensive tool that provides past and current streamflow data in real time. It supports data visualization in form of graphs, tables, and maps [119]. WaterWatch is used to produce multiple stream maps with following features:

- 30 years of location data of approximately USGS 3000 streams gages
- Color maps for streamflow conditions and historical streamflow
- GUI to get stream stage (water elevation) and flow graphs
- identification of location of occurrence of extreme hydrologic events (e.g., floods and droughts)
- The real time, average daily, and 7-day average streamflow stream gage-based maps with flood, drought, high flow, and below-normal conditions
- Support for hydrologic unit code (HUC), the stream gage-based maps in hydrologic regions

A list of tools in the WaterWatch toolkit is given in Table 4.2 [117, 119].

Table 4.2 Tools in WaterWatch toolkit [117, 119]

WaterWatch tool	Description
Hydrologic unit runoff maps	Hydrologic unit runoff and runoff condition maps from 1901 to 2015
Rating curve	Streamflow rating curve
Runoff hydrograph	Runoff time-series plots
Streamflow conditions map	Streamflow conditions
Streamflow map animation	Real-time streamflow and flood-and-high flow maps
Raster hygrograph	Pixel-based plots for visualizing and identifying variations and changes in a streamflow data set
Seven-day low flow conditions	Seven-day low flow of an area for a specific period
Streamgage statistics	Statistics and a duration graph for a streamgage
Streamflow measurements	Streamflow measurements for a period and in an area
Flood-tracking chart	Flood stages with recorded peak stages of previous floods
Streamgage finder	Streamgages by region and river name
Flood and high flow	Table listing flood, high flow, and peak rank summary
Streamflow map viewer	Dynamic maps
Cumulative area-based runoff hydrograph	Graphical presentation of cumulative daily area-based runoff, plotted over the cumulative long-term statistics (median and interquartile range) of runoff
Duration hydrograph	Time-history of streamflow

4.7.6 *Water Evaluation and Planning System (WEAP)*

The WEAP is used for integrated planning assessments of different components of the water system and supports water planning, simulations, and water resources management tool [106]. Its robust integrated engines consider water quality, supply and demand, and other ecological parameters in single watershed, agriculture, urban, trans-boundary river basin, and environmental systems. The important features of the system include simulation capability to many different types of components such as precipitation, runoff, rainfall, reservoirs, and groundwater recharge. At the policy level, it supports demand analysis, rights and priorities, conservation, vulnerability assessment, hydro-power generation, and water quality. It can also provide the cost/benefit analysis of the simulated systems with various stakeholders engagement. The component of the WEAP is

- Water Balance. A database for water demand and supply data.
- Simulation Based. Supports simulations of various hydrologic and policy cases.
- Policy Scenarios. Policies to develop and manage water systems.
- User-Friendly GUI. A GUI to support multiple model output formats (e.g., tables, maps, and charts).
- Model Integration. Supports import and export from other models.

4.7.7 *CalWater*

The CalWater [27] deals with the empirical measurements of two vital factors: atmospheric rivers (ARs) and aerosols [12, 29, 81, 98, 108], in eastern Pacific coastal region. The evaluation of these two parameters is important to understand variations in extreme precipitation events and water supply. The atmospheric rivers (ARs) [27, 49, 64, 65, 73, 77, 86–89, 102, 102, 104, 121, 124, 125] deliver significant water vapor related to major storms. Similarly, the aerosols (local and remote) impact the precipitation events in these coastal areas.

4.7.8 *River and Reservoir Modeling Tool (RiverWare)*

The RiverWare is an advanced tool that is used for water resources modeling (e.g., river basin and reaches, reservoir, hydrologic processes, distribution canals, hydro-power production and uses, water quality, and diversions) [1]. It is also a decision making tool with real-time operations support and policy based simulations and post-processing. Another important feature of the RiverWare is the problem solution and optimization engine under temporal and spatial constraints and scenarios. For this purpose, the RiverSMART is used that is software framework to create, execute, and archive the big RiverWare study plans based hydrologic ensemble, needs, and strategic directions of water supply and use. The policy analysis, demand input, and study manager are other important tools of RiverWare.

4.7.9 Digital Coast

The digital coast provides data and tools for coastal services including coastal water quality, land cover, shoreline, and surface water. It helps coastal management community to address climate and water related issues [76].

4.7.10 European CoastColour

The purpose of CoastColour is to provide measurements and data that is relevant to coastal zone management at 300 m spatial resolution along with processing algorithms for different coastal water types [26]. It is useful to obtain data about sea level, carbon cycle, and water mass distribution. It can also be utilized to develop and validate the various coastal water algorithms (water leaving reflectance). The CoastColour data set is available on-line.

4.7.11 Water Harvesting Assessment Toolbox

The water harvesting assessment toolbox is used in understandingand development of the water harvesting processes to meet the water related challenges [118]. It is also decision support tool to get better insights in water harvesting and supports various water harvesting techniques and system implementation.

4.7.12 National Groundwater Monitoring Network

The National Ground-Water Monitoring Network (NGWMN) is a network of groundwater monitoring wells across the US [74]. It is one of the critical networks to meet the needs of water research community about groundwater data, which is otherwise unavailable data. It supports various databases of past and current information of about water quality, water level, physical characteristics of rocks (lithology), and well composition. It is used to assess the water level declines.

A list of sustainable water IoT databases and systems with their sensing parameters is given in Table 4.3.

Table 4.3 Sustainable water IoT databases and systems

Sensing	System	Description
Meteorological data	Global historical climatology network-daily (GHCN-D)	Meteorological data from satellites and radars
Streamflow	NOAA national water information system (NWIS)	Streamflow data for water and planning purpose
Water temperature and quality	NorWest	Historical data about water temperature and quality
Chemical, physical, and biological properties	National stream internet	Geo-statistical data
Meteorological data	Quality controlled local climatological data (QCLCD)	Global Meteorological data of climate variables
Precipitation	Precipitation frequency data server (PFDS)	
Integrated water modeling	National water model	Hydrologic forecasting system of atmospheric conditions and their connection to river and streamflow
Soil moisture	Soil climate analysis network (SCAN)	Soil moisture monitoring
Snow	Snow survey and water supply forecasting	Real-time air temperature, precipitation, and snow-pack information
Groundwater	National GW monitoring network	Groundwater for climate forecasting
Wetlands	National wetland inventory 2.0	Geo-spatial data and wetland maps and properties
Water use	NWISWeb	Water use data
Atmospheric	FLUXNET	Exchange of CO_2, water vapor, and energy
Water and human health	The waterborne disease and outbreak surveillance system	waterborne disease and outbreaks
Water and aquatic animal health	National wildlife health survey database	Aquatic animal health in the wild
Daily forecast and models	Network for environment and weather applications	Interactive forecast models

4.7.13 Water Toolbox

The water toolbox is a data portal for integrated water resources management. It provides state-of-the-art tools, models, best management practices, legislative resources, policy guidelines, and comprehensive data sets to the international water community for education and research purpose.

Other water related tools to support real-time decision making in sustainable water IoT are discussed below [112]:

- SSMI Water Vapor Imagery. Latest integrated water vapor, cloud liquid water, and rain rate.
- GOES West Satellite Imagery. Infrared, visible, and water vapor satellite images.
- AR Precipitation Observations. Gridded precipitation products at several timescales.
- Atmospheric River Observatories. Analyses of water vapor flux, radar and disdrometer, and snow level.
- Integrated Water Vapor. An experimental tool using NCEP's GFS and NAM systems
- Probabilistic Landfall Tool. The magnitude, probability, and timing of West Coast AR conditions.
- Integrated Water Vapor Flux. An experimental tool using NCEP Global Forecast System.
- Precipitation Forecasts. The quantitative precipitation forecasts from NCEP/WPC & GFS.

4.8 Sustainable Water Indices

The major indices are given below:

- The water footprint. The water footprint is an index of the volumes of freshwater appropriated/consumed/polluted by the humanity. Its measurement is presented by using the matrix format at spatio-temporal scale. The water footprint combined with other economic, social, and environmental data is a good indicator of water sustainability including SGD goal assessment.
- The U.S. Climate Extremes Index is a US index of extreme conditions. The long-term values of this index indicate the tendency for extremes climate.
- Watershed Analysis Risk Management Framework (WARMF). The Watershed Analysis Risk Management Framework (WARMF) is a general tool to model and analyze the watershed and can be used with different watersheds. It is utilized for short- and long-term prediction process, management of watersheds, and in calculation of total maximum diurnal load.

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