Point-Based Groundwater Monitoring: *History*

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The initial type of groundwater investigation started with level measurements with different types of instruments. These methods and instruments include steel tape, electronic measuring tapes, pressure transducers, sounding devices, test drilling, geophysical investigation techniques, piezometers, digital water level recorders, exploratory well drilling, and isotopes, etc.

groundwater monitoring   point based monitoring   Geophysical Investigation Techniques

1. Wells and Piezometers

Agricultural and domestic wells can be used for measuring groundwater levels [23 (https://www.mdpi.com/2073-4441/14/4/565/htm#B23-water-14-00565),24 (https://www.mdpi.com/2073-4441/14/4/565/htm#B24-water-14-00565),25 (https://www.mdpi.com/2073-4441/14/4/565/htm#B25-water-14-00565)]. Normally, piezometers are utilized to gage the water level in wells to find out the hydraulic head. Normally, annual groundwater level changes are assessed with point-based groundwater-level observation wells [26 (https://www.mdpi.com/2073-4441/14/4/565/htm#B26-water-14-00565)].

Digital Water Level Recorders (DWLRs) are mounted in several piezometers that help in better understanding of the groundwater system and of the recharge in various hydrogeological conditions. Generally, water-level measurement data from boreholes or piezometers/monitoring wells are used for making the water table or potentiometric surface maps [27 (https://www.mdpi.com/2073-4441/14/4/565/htm#B27-water-14-00565),28 (https://www.mdpi.com/2073-4441/14/4/565/htm#B28-water-14-00565)]. These are further used to find groundwater flow direction, groundwater-level recovery ensuing a pumping event, or to find out other aquifer properties. For water-quality monitoring, the piezometer is also a reliable source for groundwater sampling from the tapped aquifer [29 (https://www.mdpi.com/2073-4441/14/4/565/htm#B29-water-14-00565)].

2. Conventional Instruments

Steel tape can be considered the oldest yet the most accurate technique of measuring the water levels [30 (https://www.mdpi.com/2073-4441/14/4/565/htm#B30-water-14-00565),31 (https://www.mdpi.com/2073-4441/14/4/565/htm#B31-water-14-00565)]. Steel tape works by gradually lowering the tape mounted with a weight into the well. Before lowering, chalk on the lower few feet of the tape identifies the part of the tape that was submerged. A feel is developed for the weight of the tape when it is lowered into the well. The reading is then recorded once it is confirmed that the tape's lower end touches the water surface in the well. Then, the tape is rapidly brought to the ground surface before the wetted chalk mark dries and becomes difficult to read. The submerged portion of the tape is then measured and adjusted in the final reading of the tape [32 (https://www.mdpi.com/2073-4441/14/4/565/htm#B32-water-14-00565)]. This method is mostly accurate for the water levels found at less than 200 feet below the ground surface. At more than 500 feet of depth, thermal expansion and stretch in the steel tape begins [33 (https://www.mdpi.com/2073-4441/14/4/565/htm#B33-water-14-00565)].

Steel tape has been developed into electronic measuring tapes or tape sounders, which are made up of a pair of separated insulated wires. Well dippers and sounding devices with acoustic and light signs are practical and extensively used to check groundwater levels more accurately and quickly [34 (https://www.mdpi.com/2073-4441/14/4/565/htm#B34-water-14-00565)]. Sounding devices work by reeling the tape down the well with care, avoiding the casing's sides. The probe holder is swiveled on the frame of the water level meter to let the tape move unrestricted down the well. When the system sounds, the reading of the depth to water is measured with care. The probe is raised and lowered in and out of the water to obtain a consistent outcome [32 (https://www.mdpi.com/2073-4441/14/4/565/htm#B32-water-14-00565)].

The use of pressure transducers and automatic data loggers speed up the measurement process and enable monitoring the fluctuations over time [35 (https://www.mdpi.com/2073-4441/14/4/565/htm#B35-water-14-00565)]. These are mounted in the piezometers, which help in observing temporal variations of hydraulic head [36 (https://www.mdpi.com/2073-4441/14/4/565/htm#B36-water-14-00565)]. These can provide long-term or continuous monitoring of groundwater levels. Gray and Mahapatra [37 (https://www.mdpi.com/2073-4441/14/4/565/htm#B37-water-14-00565)] anticipated that these can be used not only to determine the situation of the groundwater table but the hydraulic conductivity of a soil as well. The probes are most suitable in heavy soils since the water table position can be calculated without having true static circumstances.

The working of a pressure transducer starts by taking a reading from the pressure transducer before placing it into the well. There are two types of pressure transducers: vented and non-vented. For a vented pressure transducer, the reading is taken as zero, and for a non-vented pressure transducer, this is a positive number, which is equal to atmospheric pressure. In case of non-vented pressure transducer, its reading should be the same as that of a reading from the barometric pressure transducer. Then, the pressure transducer is lowered into the well gradually [32 (https://www.mdpi.com/2073-4441/14/4/565/htm#B32-water-14-00565)]. Field calibration of the pressure transducer is carried out by raising and lowering it over the estimated range of water-level variation. Two readings at each of five intervals are taken: one during the raising and the other at the time of lowering the pressure transducer. The static water level in the well is measured with steel tape or electric sounding tape and the readings compared; if the measurements are not consistent within 0.02 feet, then the reading are repeated. In the case of the non-vented pressure transducer, the barometric pressure from the transducer pressure is subtracted to acquire the water-level pressure. This water-level pressure is then multiplied by 2.3067 to convert from psi (pounds per square inch; pressure unit) of pressure to feet of water [38 (https://www.mdpi.com/2073-4441/14/4/565/htm#B38-water-14-00565)].

The use of the point-based conventional technique is widespread in Managed Aquifer Recharge techniques, from basic arrangements of pressure transducers to monitoring groundwater level changes to complex arrangements of sensors, including also physico-chemical ones [39 (https://www.mdpi.com/2073-4441/14/4/565/htm#B39-water-14-00565)]. This technique is in operation in Italy; however, it needs appropriate tools for its management.

Rosenberry et al. [40 (https://www.mdpi.com/2073-4441/14/4/565/htm#B40-water-14-00565)] identified that scale, accuracy, and sources of error are the main factors that determine the selection of an appropriate method for groundwater monitoring.

3. Geophysical Investigation Techniques

Geophysical investigation techniques include electrical resistivity survey, seismic, gravity, and magnetic methods. These methods are one step ahead of the above-mentioned techniques, as a borehole is not always required, and therefore, they can be used in variety of geological conditions. However, borehole data are used to validate the results and interpretations of geophysical surveys to enhance the precision of in situ data analysis [41 (https://www.mdpi.com/2073-4441/14/4/565/htm#B41-water-14-00565)].

Electrical resistivity surveys are used to find the subsurface resistivity distribution by making measurements on the ground surface. By combining geophysical data with lithological information, electrical conductivity (EC) logs through the wells, and hydro-chemical data, electrical resistivity with groundwater EC values can be interpreted to identify the freshwater-saturated zones [42 (https://www.mdpi.com/2073-4441/14/4/565/htm#B42-water-14-00565)].

The ground resistivity is dependent on many geological factors, for example, the mineral and fluid content, porosity, and amount of water saturation of the rock. The electrical resistivity survey is a preferable geophysical method for groundwater investigation. Many authors used this tool for groundwater investigation [43 (https://www.mdpi.com/2073-4441/14/4/565/htm#B43-water-14-00565),44 (https://www.mdpi.com/2073-4441/14/4/565/htm#B44-water-14-00565),45 (https://www.mdpi.com/2073-4441/14/4/565/htm#B45-water-14-00565),46 (https://www.mdpi.com/2073-4441/14/4/565/htm#B46-water-14-00565),47 (https://www.mdpi.com/2073-4441/14/4/565/htm#B47-water-14-00565),48 (https://www.mdpi.com/2073-4441/14/4/565/htm#B48-water-14-00565)]. Electrical resistivity surveys are used to determine the vertical changes between the bottom of the earth's the electrical resistance and potential field produced by the current. This method includes the electric current induced into the ground through two embedded electrodes and measures the potential difference between the two other electrodes denoted as the potential electrodes. The current electricity used is the direct current provided by the dry cell. Therefore, the analysis and explanation of geologic data is on the basis of resistivity value. The resistivity is calculated from the measured induced currents and the potential difference. It is assumed here that the soil is uniform, but in reality, the earth's resistivity is determined by homogeneous lithology and geological configuration. Consequently, the graph between the resistivity and the current electrode distance is used to find the vertical changes in the resistance development. Explanation of this graph gives the depth of sand, which is used to confirm the existence of aquifers or groundwater in the area [49 (https://www.mdpi.com/2073-4441/14/4/565/htm#B49-water-14-00565)].

Seismic techniques have great potential for hydrogeological studies and depend upon the physical characteristics of the earth that produce electrical signals from the seismic waves [50 (https://www.mdpi.com/2073-4441/14/4/565/htm#B50-water-14-00565)]. Seismic waves follow the same laws of propagation as light rays and may be reflected or refracted at any interface where velocity change occurs. Seismic reflection methods provide information on geologic structure thousands of meters below the surface, whereas seismic refraction methods are useful for depths up to 100 m.

Seismic techniques depend on measurements of the time interval between the beginning of a seismic wave and its appearance at detectors. The seismic waves are produced by different means, such as by an explosion, a dropped weight, a mechanical vibrator, a bubble of high pressure air injected in water, etc. The seismic waves are sensed by a geophone on ground and by a hydrophone in water. An electromagnetic geophone produces a voltage when a seismic wave generates relative motion of a wire coil in the magnetic field, while a ceramic hydrophone generates a voltage when deformed by passage of a seismic wave. Data are usually recorded on magnetic tape for subsequent and processing and display [51 (https://www.mdpi.com/2073-4441/14/4/565/htm#B51-water-14-00565)].

Similarly, the gravity method is a broadly used geophysical technique for discovering mineral resources and groundwater based on the deviation in gravity, which varies with the density of soil. This method is quite helpful for sedimentary terrains. The magnetic method detects the earth's magnetic fields, which can be measured/mapped. As magnetic contrasts are seldom associated with groundwater occurrence, this method can be used along with the gravity method to shortlist the possible underground options.

Gravity method of geophysics determines the difference in the earth's gravitational field at a defined site owing to the rock mass characteristic. This technique is appropriate for near surface groundwater investigations. As the gravity is directly proportional to mass, the difference between the two rocks' masses gives notable anomaly in the earth's gravity field. If this anomaly is suitably measured, it can be used to assess the thickness of the unconsolidated rock [52 (https://www.mdpi.com/2073-4441/14/4/565/htm#B52-water-14-00565)]. In crystalline rock topography, the unconsolidated rock generally forms a groundwater aquifer due to high porosity, permeability, and transmissivity [48 (https://www.mdpi.com/2073-4441/14/4/565/htm#B48-water-14-00565)]. Gravimeter Scintrex CG-5 was applied for gravity measurement in a case study in Semarang City, central Java, Indonesia [53 (https://www.mdpi.com/2073-4441/14/4/565/htm#B53-water-14-00565)].

The tools, such as electrical resistivity, seismic, and gravity methods, are normally applied for detailed groundwater investigations. The most standard and reliable geophysical techniques are test drilling and stratigraphy analysis; however, these techniques of groundwater exploration are neither cost nor time effective and frequently require trained professionals [41 (https://www.mdpi.com/2073-4441/14/4/565/htm#B41-water-14-00565)].

Another method, "time-lapse gravity survey," was applied to the monitoring of an artificial aquifer storage and recovery (ASR) system in Lyden, Colorado [54 (https://www.mdpi.com/2073-4441/14/4/565/htm#B54-water-14-00565)]. Through this method, all steps of the method were studied systematically that involve survey design, data acquisition, processing, and quantitative interpretation.

4. Monitoring of Aquifer Recharge Rate

Information on groundwater age is essential to address features, for example, recharge rates and mechanisms, resource renewability, flow rates, and vulnerability to pollution. Monitoring of these parameters becomes essential when dealing with shared water resources [19 (https://www.mdpi.com/2073-4441/14/4/565/htm#B19-water-14-00565)]. Exploratory well drilling with the use of isotopes is used for monitoring these parameters [19 (https://www.mdpi.com/2073-4441/14/4/565/htm#B19-water-14-00565),55 (https://www.mdpi.com/2073-4441/14/4/565/htm#B55-water-14-00565)]. Stable and radioactive environmental isotopes provide information on the geochemical processes of groundwater and the hydrogeological characteristics of aquifers. Traditionally, groundwater flow patterns are inferred from indirect investigations. For example, nitrate concentration, often associated with agricultural activities, is used to identify the characteristics of shallow aquifers' groundwater supplies [56 (https://www.mdpi.com/2073-4441/14/4/565/htm#B56-water-14-00565)]. Another indirect technique for groundwater recharge is used in the arid region of Saudi Arabia [57 (https://www.mdpi.com/2073-4441/14/4/565/htm#B57-water-14-00565)], in which authors found about 55–70% of rainwater infiltrated though soil profile and was recharged in underlined groundwater reservoir, which finally becomes a major source of water in the region.

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