Coastal Zone Monitoring Protocols

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INTRODUCTION

Coastal populations and industries require a host of natural resources for sustenance, one of the most important of which is a reliable source of freshwater. As groundwater use has increased in coastal areas, so has the recognition that groundwater supplies are vulnerable to overuse and contamination. Groundwater development depletes the amount of groundwater in storage and causes reductions in groundwater discharge to streams, wetlands, and coastal estuaries and lowered water levels in ponds and lakes. Contamination of groundwater resources has resulted in degradation of drinking water supplies and coastal waters. Although overuse and contamination of groundwater are not uncommon throughout our country, the proximity of coastal aquifers to saltwater creates unique issues with respect to groundwater sustainability in coastal regions. These issues are primarily those of saltwater intrusion into freshwater aquifers and changes in the amount and quality of fresh groundwater discharge to coastal saltwater ecosystems.

OCCURRENCE AND FLOW OF FRESHWATER AND SALTWATER IN COASTAL AQUIFERS

Groundwater occurs in pores, fractures, solution cavities, and other openings in geologic formations that underlie the coastal zone. The nature of the water-bearing openings within a specific geologic formation depends to a large extent on the mineral composition and structure of the formation and the geologic processes that initially formed and then further modified it. Although numerous types of geologic formations exist along the coastal zone, the most important water-bearing formations are unconsolidated sands and gravels; semiconsolidated sands; and, among the consolidated rocks, carbonates (primarily limestones), sandstones, and fractured rocks.

The general pattern of fresh groundwater flow in coastal aquifers is from inland recharge areas (where groundwater levels typically are highest) to coastal discharge areas (where groundwater levels are lowest). Fresh groundwater comes in contact with saline groundwater at the seaward margins of coastal aquifers. The seaward limit of freshwater in a particular aquifer is controlled by the amount of freshwater flowing through the aquifer, the thickness and hydraulic properties of the aquifer and adjacent confining units, and the relative densities of saltwater and freshwater, among other variables. Because of its lower density, freshwater tends to remain above the saline zones of the aquifer, although in multilayered aquifer systems, seaward-flowing freshwater can discharge upward through confining units into overlying saltwater. Generally, saltwater is defined as water having a total dissolved-solids concentration (TDS) greater than 1,000 mg/L. Seawater has a TDS concentration of about 35,000 mg/L, of which dissolved chloride is the largest component (about 19,000 mg/L).

Sources and Chemical Characteristics of Saltwater

All water contains dissolved chemical materials termed 'salts'. When the concentration of these dissolved materials becomes large, the water is referred to as 'saltwater' or as 'salty', 'brackish', or 'saline'. Brackish waters can be defined as water having a TDS concentration of 1,000 to 35,000 mg/L. The upper concentration limit for brackish water is set at the approximate concentration of seawater (35,000 mg/L). The average concentrations of the major dissolved constituents of seawater are given in Table 1; chloride, sodium, sulfate, and magnesium have the largest concentrations. Water with a dissolved solids concentration exceeding that of seawater is termed as brine. Although there are different types of brines in terms of chemical composition, the largest number represents concentrated seawater containing mostly sodium chloride. Because of the high concentration of chloride in seawater (19,000 mg/L), less than 2% contribution of seawater mixed with fresh groundwater can render the water unsuitable for public supply.

Two additional characteristics of water that are important in groundwater systems are density and viscosity, both of which are dependent on the type and amount of solutes dissolved in the water. Density is important because it is part of the driving force that defines the direction and rate of fluid movement through a groundwater system; moreover, density and viscosity of the water affect the hydraulic transmitting properties of the groundwater system, which influence the rate of fluid movement. Although seawater in the ocean and estuaries are by far the primary source of saline water to coastal groundwater systems, a number of other sources can affect coastal groundwater quality. These sources include:

- Precipitation: Oceans are the largest single source of salts in the atmosphere, and sodium and chloride are the most abundant ions in air masses over the sea. Chloride and sodium concentrations, therefore, are high in air masses near sea coasts but decrease rapidly with increasing distance inland. These airborne salts are delivered to coastal watersheds by precipitation. Chloride concentrations in precipitation, however, are relatively small compared to seawater. Concentrations of sodium and chloride can be increased in soils, shallow surface waters (such as tidal lagoons), and groundwater by evaporation and evapotranspiration.
- Sea-spray accumulation, tides, and storm surges, which can be local sources of increased groundwater salinity in low-lying coastal areas.
- Entrapped fossil seawater in unflushed parts of an aquifer: Such water either was trapped in geological formations when they were deposited (connate water) or flowed into the formations during periods of relatively high sea levels when seawater flooded low-lying coastal areas.
- Dissolution of evaporitic deposits such as halite (rock salt), anhydrite, and gypsum.
- Pollution from various anthropogenic sources including sewage and some industrial effluents, oil- and gas-field brines brought to the land surface during exploration and production, and return flows of irrigation water.

The freshwater and saltwater zones within coastal aquifers are separated by a transition zone (also referred to as the zone of dispersion) within which there is mixing between freshwater and saltwater (Fig. 1). The transition zone is characterized most commonly by measurements of either the TDS concentration or of the chloride concentration of groundwater sampled at observation wells. Although there are no standard practices for defining the transition zone, concentrations of TDS ranging from about 1,000 to 35,000 mg/L and of chloride ranging from about 250 to 19,000 mg/L are common indicators of the zone. In other words, the term "transition zone" implies a change in the quality of groundwater from freshwater to saltwater, as measured by an increase in dissolved constituents such as total dissolved solids and chloride.

Table 1. Average concentration of major dissolved constituents of seawater

Constituent	Concentration (mg/*l*)
Chloride	19,000
Sodium	10,500
Sulfate	2,700
Magnesium	1,350
Calcium	410
Potassium	390
Bicarbonate	142
Bromide	67
Strontium	8
Silica	6.4
Boron	4.5
Fluoride	1.3

Within the transition zone, freshwater flowing to the ocean mixes with saltwater by the processes of dispersion and molecular diffusion. Mixing by dispersion is caused by spatial variations (heterogeneities) in the geologic structure and the hydraulic properties of an aquifer and by dynamic forces that operate over a range of time scales, including daily fluctuations in tide stages (Fig. 2), seasonal and annual variations in groundwater recharge rates, and long-term changes in sea level position. These dynamic forces cause the freshwater and saltwater zones to move seaward at times and landward at times. Because of the mixing of freshwater and saltwater within the transition zone, a circulation of saltwater is established in which some of the saltwater is entrained within the overlying freshwater and returned to the sea, which in turn causes additional saltwater to move landward toward the transition zone (Fig. 1).

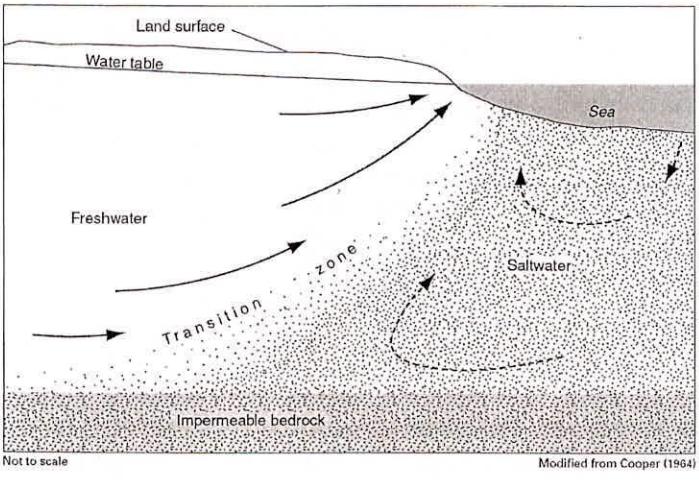

Fig. 1 Groundwater flow patterns and the freshwater-saltwater transition zone in an idealized coastal aquifer.

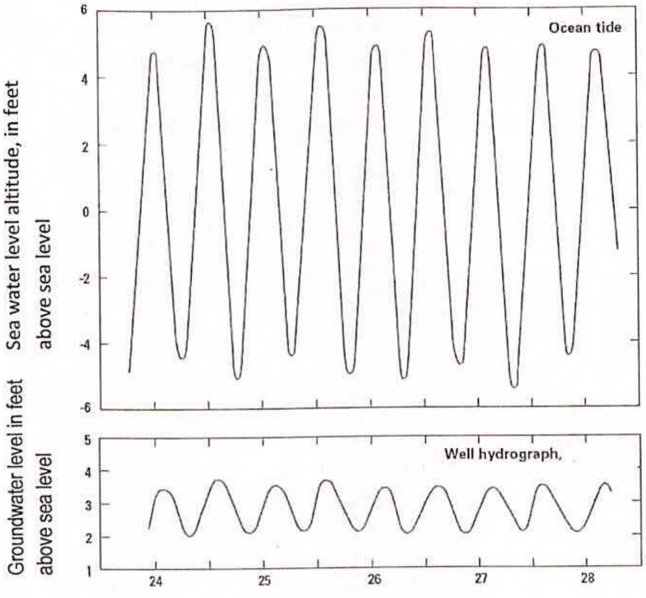

Fig. 2 Mixing of freshwater and saltwater in the transition zone is caused in part by the forces of rising and falling ocean tides. Tidal fluctuations also cause cyclic fluctuations of groundwater levels near the coast. The tidal fluctuations are transmitted hydraulically into the freshwater aquifer and cause water level fluctuations in the well that are of similar frequency but smaller amplitude. The effect of tidal fluctuations is most pronounced at the shoreline and decreases rapidly with increased distance inland from the coast.

SALTWATER INTRUSION

Saltwater intrusion is the movement of saline water into freshwater aquifers and most often is caused by groundwater pumping from coastal wells. Because saltwater has high concentrations of total dissolved solids and certain inorganic constituents, it is unfit for human consumption and many other anthropogenic uses. Saltwater intrusion reduces fresh groundwater storage and, in extreme cases, leads to the abandonment of supply wells when concentrations of dissolved ions exceed drinking-water standards. A judicious groundwater management plan and ongoing monitoring in coastal zones is very much needed to ensure that the quality and quantity of the groundwater resource are not adversely affected. A carefully planned coastal hydrologic monitoring system may have following objectives:

- a comprehensive monitoring dataset on groundwater levels and water quality to enable robust analysis of coastal groundwater system that will contribute to knowledge development on how to better manage fragile coastal systems faced with rising demand;
- integration of water quantity and quality considerations within a risk management framework to evaluate sustainable extraction regimes for coastal groundwater systems and, in particular to consider the risk of saline upconing and seawater intrusion;
- improved understanding of sustainable extraction regimes particularly during peak competing demand periods;

- improved management of aquifers for long-term sustainable use, providing pathways for minimising aquifer stress, and improved assessment of new opportunities for coastal groundwater development that is environmentally sustainable;
- trade-offs between consumptive groundwater use and the requirements of dependent ecosystems in coastal regions by combining seawater intrusion models and applying indicators and socioeconomic analysis.

In order to understand, protect and restore the coastal groundwater, a monitoring program can be designed under the following framework:

- Develop monitoring objectives
- Design monitoring program
- Collect field and lab data
- Compile and manage data
- Assess and interpret data
- Convey results and findings

MONITORING FRAMEWORK

A monitoring framework is essential to the design and adaptation of an effective monitoring program. It establishes a simple sequential structure that encourages thoroughness, facilitates communication within and between different levels of operation and management, and provides overall direction and focus that is essential to achieving success in large-scale and long-term studies in coastal areas. An example of a monitoring framework is illustrated in Fig. 3.

There are three core phases to the monitoring process, namely, planning, sampling and analysis, and management and reporting. Each of these phases is made up of several component steps, described below.

Define Monitoring Objectives

A monitoring program is motivated by the need to assess, protect, understand and manage water availability or quality issues or other ecological or environmental issues. In order to do this effectively it is critical that these issues are well defined and understood. This knowledge dictates the type of information and data that the monitoring program must provide. While some monitoring programs may be developed around a single issue, the design of an integrated monitoring program invariably seeks to provide information and knowledge on multiple issues. It is important that the requirements and interests of all stakeholders, including managers, government organisations, industry groups, community groups and the wider public, be canvassed surrounding the specific environmental issues as they may bring different perspectives.

A conceptual model of the operating underlying processes is often an essential developmental step because it is a powerful and simple way to represent the current understanding of how the system is functioning. It identifies relationships between elements of the system and represents those factors that are considered to be causing changes. It also provides something we can readily relate our findings to after the monitoring data are collected and analysed. A conceptual model is often found to be a valuable communication tool.

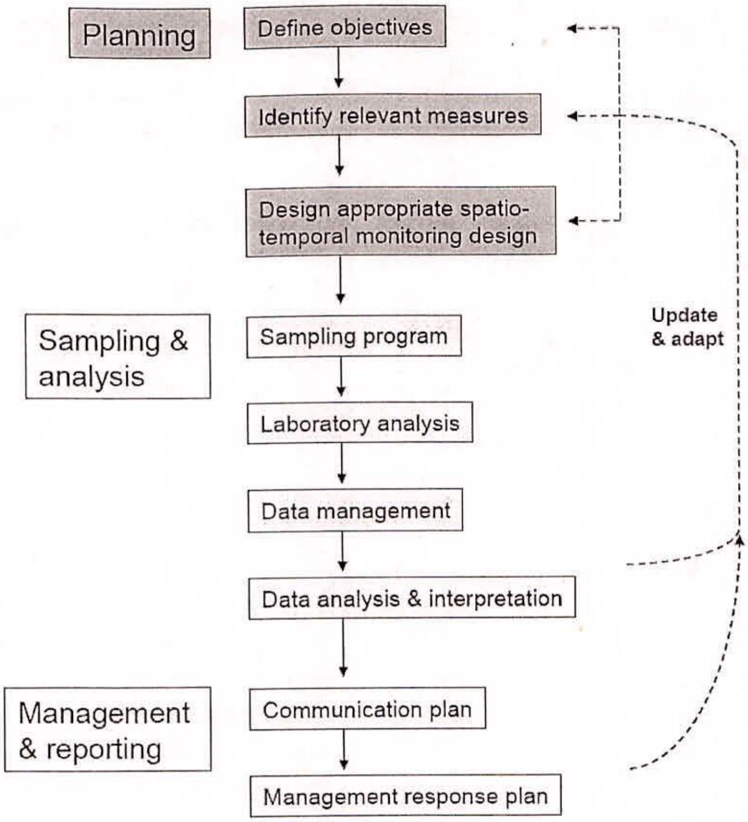

Fig. 3 Illustration of a monitoring framework

The monitoring objectives need to be explicit, concise and well-defined. This helps ensure that the monitoring program is targeted and appropriate. Well-defined objectives thus provide the focal point for considerations in all subsequent components of the monitoring process.

Appropriate Spatio-Temporal Monitoring Design

The spatio-temporal design is a fundamental step in the monitoring process. It determines the specific nature of sampling that is required to address the monitoring objectives. Through an appropriate spatio-temporal design, we aim to identify the

- location and number of sampling sites,
- required frequency and timing of sampling,
- need for stratification in the design to take into account known underlying physical or environmental processes and therefore improve inference,
- sample collection and analysis methods, including the level of precision necessary,
- equipment needs,
- methods to be used for data analysis, and
- human resource requirements.

These decisions will need to carefully balance the inherent natural spatial and temporal variability in the system, the size of the change that needs to be detected (the effect size), physical constraints pertaining to large-scale monitoring and the potential size of the sampling domain, and the cost involved with sampling. All-in-all, the spatio-temporal design must be effective, achievable and affordable.

Highly variable systems will require more sampling and/or well-timed sampling (i.e. after an event) to distinguish any change from the background variation and to establish peak concentrations of particular parameters. Monitoring designs can be costly and often have a tendency to become unaffordable. It is imperative that the resource constraints are transparent at the outset. It will often be necessary to establish priorities amongst the objectives. This might, for instance, involve sampling more frequently at locations that are expected to respond to changes in hydrologic stresses and less frequently at sites that are not impacted by these pressures.

Sampling

It is essential that the sampling is undertaken according to standard protocols and methods as this helps ensure reliability and consistency. The methods that are used and the equipment required need to be carefully considered and communicated. Calibration procedures may be necessary in order to prevent any drift in the measurement due to equipment fouling. It is important that detailed documentation be kept of the sampling. This includes recording the key attributes like the location and timing of the sample, the method and equipment used, and whether there were any exceptional circumstances related to the collection. Any information on data quality should be noted where possible. This is particularly important for samples that are taken in the field and analysed later in the laboratory when no recourse is possible. Procedures need to be established for the appropriate storage of samples prior to analysis.

Laboratory Analysis

The processing of samples in laboratories can involve complicated analytical procedures and needs to be performed according to standard protocols to ensure reliability and consistency. Detailed documentation of laboratory samples and analyses is important.

Data Management

Data should be archived for future data analysis and interpretation. It is essential that a data management system that is reliable, practical, efficient and incorporates GIS capabilities be adopted. Data management should also be viewed in a broad sense and the system should incorporate more than just quantitative information. For instance, it is important to keep thorough records of all management interventions as part of the data management exercise.

Data Analysis and Interpretation

Data analysis is a fundamental component of a monitoring program. It is often necessary to conduct some exploratory data analysis early on in a monitoring study to ensure data integrity and reconcile the collected data with expectations. Some data preparation, such as removal of obvious erroneous observations or data transformation, is often necessary prior to analysis. The appropriate statistical and mathematical analyses should be decided in the design phase, and well before the data is collected, because carefully considered data analysis may have implications for the spatio-temporal monitoring design and help ensure that we maximize our opportunity to address the objectives. That said, statistical and mathematical modeling are often an iterative process and the analysis should be adapted to best suit the data and collection characteristics. The data analysis should then be interpreted in relation to the monitoring objectives. What implications does the data analysis have? Has it altered our conceptual understanding of the system?

Communication and Management Response

The results and findings from the monitoring program need to be reported to interested stakeholders. As the requirements of individual stakeholders will not all be the same there will be a need to tailor the communication so that it is relevant. For instance, a report for a scientific audience would be pitched differently to one that is delivered to policy makers. In all cases the report should be concise, informative and centre on the defined monitoring objectives and how the study is addressing these. Visualisation and graphical techniques are valuable for summarising the information content and conveying the main messages succinctly. The analysis of the monitoring data may trigger a management response. It could involve a decision to commission a separate research study to improve understanding of a specific aspect. All management interventions need to be adequately documented and assessed against observed changes.

Review and Refinement of Monitoring Program

Objectives and monitoring programs evolve with time. It is important to incorporate feedback loops into the monitoring program so that it may be manipulated to reflect changing needs. The specific details of the required frequency of this review process are dependent on numerous factors, e.g. review can take place as part of any annual reporting. More frequent or less frequent review may also depend on the frequency of the sampling. For instance, if aerial photographs are commissioned every five years it is sensible to review that component on a similar interval. It is quite common for a pilot monitoring program to demand more sampling resources so that decisions on the optimal spatial or temporal resolution may be resolved by sampling at a higher intensity and considering the amount of information that is lost from sampling less intensively. Any monitoring program should aim to continuously improve with advent of new technologies, methods and knowledge. This includes reviewing and improving the underlying science and methodologies, and refining the conceptual model.

LONG-TERM HYDROLOGIC MONITORING PROTOCOL FOR COASTAL ZONE

Hydrologic features for monitoring in a coastal zone generally include: (1) groundwater, (2) ponds, (3) permanent and seasonal freshwater wetlands, (4) freshwater streams, and (5) estuarine wetlands.

Establishment of a detailed hydrologic monitoring protocol is essential for the collection of high-quality data that can be used to address current and future hypotheses and identify trends in complex data sets. Because changes in many hydrologic observations are near the limits of measurement error, each measurement must be carried out according to a specific protocol to ensure consistent data and minimize measurement error.

Specific Hydrologic Trends and Issues to Address

Long-term hydrologic monitoring is essential for understanding the effects of sea-level rise, climate change, and urbanization on the hydrologic system of the coastal zone and on the aquatic and estuarine ecosystems that depend upon that hydrologic system (Fig. 4). These 'agents of change' affect the hydrologic system in different ways and on different time scales. It is useful to explore in subsequent sections each of these agents of change briefly and to address several of the specific monitoring questions associated with these agents.

Sea-Level Rise

Sea-level change is a global phenomenon which can be modified by local conditions in the earth's crust. The response of a coastal hydrologic system to accelerated sea-level rise will likely be an increased tendency for saltwater to intrude both the underlying aquifer at depth and the tidal streams at the surface. Some of the specific hydrologic questions posed by sea-level rise are as follows:

1. Will the interface between salt and freshwater within the groundwater flow system respond immediately to accelerated rates of sea-level rise, and will this threaten existing public-supply wells?
2. How much farther inland will tidal influence and saline water penetrate the coastal streams and associated ecosystems?
3. How will the water balance of the coastal landscape be affected by sea-level rise?

Long-term hydrologic monitoring data are required to test hypotheses concerning the above questions and adopt appropriate management responses.

Climatic Change

Climate change is also a global phenomenon with distinctly local aspects that can affect hydrologic systems across a range of time scales. Drought-induced groundwater decline over an extended period (say 5 yrs) can have a large impact on the position of the interface between salt and fresh waters at the base of a coastal aquifer; the position of the interface (in the absence of pumping by humans) is directly controlled by the aquifer recharge rate, which is sharply reduced during a drought.

Some of the specific monitoring questions related to the effects of climate change on the hydrologic system are the following:

1. What are the long-term trends and periodicities in groundwater levels and how are they related to available climatic records?
2. Are groundwater, streamflow, and climatic data correlated for the common period of record and what can be inferred regarding likely ecosystem impacts of future droughts?
3. What would be the combined effects of projected sea-level rise and drought-induced recharge decline on public water supplies?

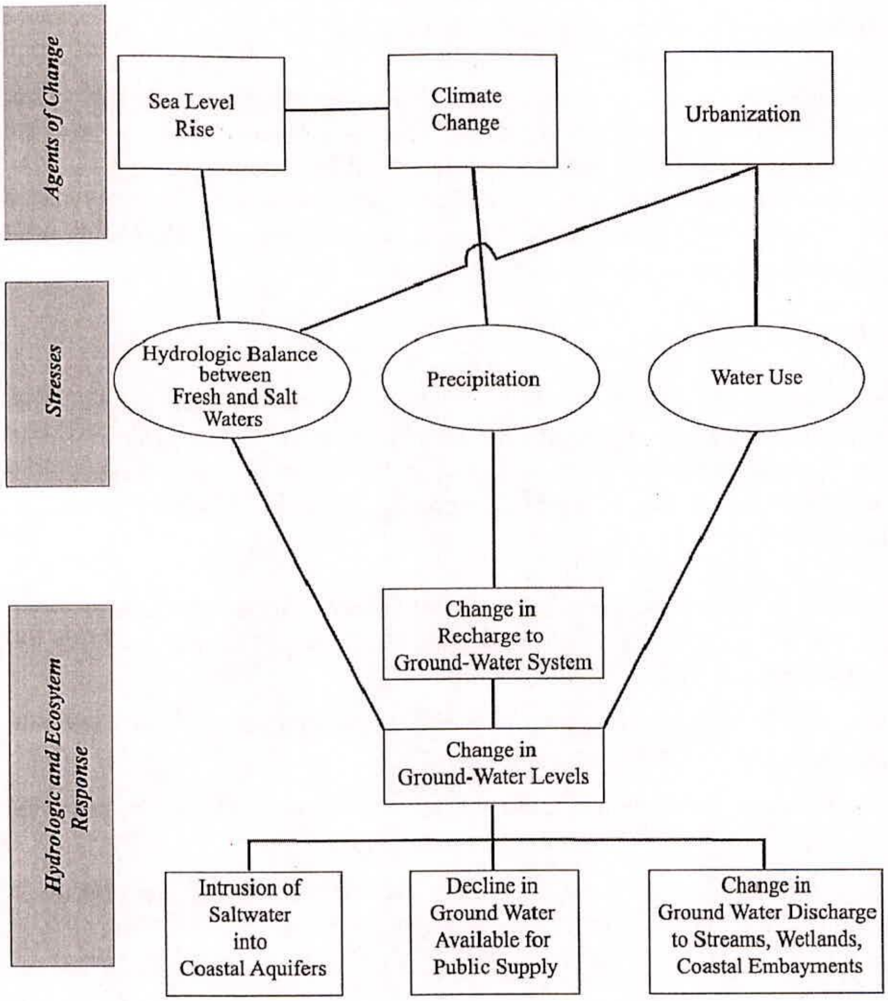

Fig. 4 Illustration of how agents of hydrologic change can stress the coastal hydrologic system and cause a variety of ecosystem responses.

Urbanization

Urbanization can affect the water balance of a coastal aquifer in several ways, with associated impacts upon human water supplies and coastal ecosystems. First, increased pumping for public-water supply or irrigation can alter the dynamic balance between fresh and saltwater in the aquifer. This pumping can lead to shifts in the position of the interface between fresh and salt waters and possibly cause saltwater intrusion into pumping wells. Second, urbanization can result in the reduction of aquifer recharge rates (and affect the interface position) by increasing the fraction of impervious surface on the landscape that generates direct surface-water runoff to coastal water bodies. Finally, urbanization can lead to exports or imports of water between adjacent flow zones in an aquifer system; these exchanges in turn affect the water balance of flow zones. Such changes in the water balance not only affect the interface between salt and fresh water at depth in the aquifer, but also have the potential to directly affect pond levels, wetland levels, streamflow, and the salinity regime of tidal creek systems.

Specific monitoring questions that need to be addressed regarding urbanization are:

1. Is there evidence that existing pumping patterns on and near the coast cause saltwater intrusion and could proposed pumping patterns cause intrusion?
2. Do land-use changes in the urbanizing areas lead to changes in recharge rates (as shown by trends in groundwater levels)?
3. What are the local drawdown effects of groundwater pumping upon ponds/ wetlands?

Sampling Methods

Monitoring sites can be categorized into three classes: (1) groundwater, (2) ponds and wetlands, and (3) streams. An optimal hydrologic monitoring network spans the region of concern with particular sites selected on the basis of clear monitoring objectives. In general, monitoring sites designed to measure the effects of global change, such as climatically induced changes in aquifer water levels, are best located in areas not influenced by local stresses to the system, such as public-supply wells.

Local effects, such as the changes in a hydrologic system caused by groundwater development, are generally best measured on a restricted scale with a greater density of monitoring sites in areas of larger stresses. An optimal monitoring network includes all types of sites spaced appropriately over the region of concern.

Groundwater

Groundwater levels within an aquifer are determined by measurements of water levels in observation wells. Mapping of the water-table surface and construction of observation well hydrographs are the most basic methods for analyzing these data spatially and temporally, and can provide information on the direction of groundwater flow, hydraulic gradients, saturated thickness of an aquifer, and spatial and temporal fluctuations in available water resources. Water-level data can assist in the interpretation of the effects of global and local agents of change, provide data for the management of water supplies, and assist with interpretations of ecological change.

Site Selection

The design of a comprehensive observation network for groundwater-level measurements requires a thorough review of existing data for the region of concern. This includes a review of existing water-table maps, well networks, water-supply studies, and published and unpublished reports. These data should be reviewed to identify: thickness and characteristics of saturated zones; depth to the water table; probable groundwater flow directions; presence of vertical gradients; hydrologic features and human stresses which may cause groundwater levels to fluctuate, such as water-supply pumping, fluctuating river stages, and tidal influence; probable frequency of fluctuations in levels; observation wells that are available for use; regions that lack previous water-table definition. General site-selection procedure and criteria are tabulated in Tables 2 and 3.

Site Selection Procedure

1. Identify the monitoring objectives and the extent of the monitoring area.
2. Identify and make inventory of existing instrumentation, public-supply wells, observation wells, and existing networks in area of interest.
3. Select sites based on minimum recommended criteria as stated in Table 2. Note that the number of sampling sites depends in part upon the amount of time budgeted per sampling round. Each monitoring field trip should be accomplished as a single "snapshot" event with no precipitation events immediately prior to or during measurements.
4. Prior to network implementation, visit field site, do depth sounding of well, check response to aquifer, and create site map. Altitude and positional surveying should be done if necessary.
5. Map network using a geographic information system. Route of shortest travel time through the network should be noted.

Table 2. General criteria for selection of observation monitoring well sites

Criteria	Rationale
Well-construction information is available	Material, depth, screen specification data are critical for well use
Well has a sound connection to the aquifer	Screened zone inside the well should be representative of the aquifer outside the casing
Hydrologic unit of well screen is known	Well operation is dependent on the geologic conditions at the screen
Well site has long-term accessibility	Multiple site visits over many years will be necessary with minimal interruption to the network
Screen is positioned near (within 20 feet of the lowest recorded water level) water table for measuring variations due to climatic changes	Screen position must provide the unconfined static water level
The monitoring well is not susceptible to going dry	Well must be operational under all hydrologic extremes of the region
In order to represent a large hydrologic area; the well occupies an optimized placement in the aquifer	With a limited number of sites possible, each site must represent a large area in the network
A detailed lithologic log is available for the borehole	Full lithologic logs provide vertical information at each site which can be used as the framework to build a hydrologic model

Table 3. Specific criteria used for choosing sites for monitoring wells

Location	Purpose
Wells located at points of inflow to the aquifer	Monitors changes in levels at the thickest part of the aquifer. Sea level effects are constant and minimal
In locations of anticipated hydrologic changes and developmental impacts	To monitor human-induced changes to the system
In locations of groundwater discharge	To monitor hydrologic changes at groundwater receivers
At locations where head definition is insufficient	To provide regional analysis of the aquifer and to define the water-table configuration
At existing sites where long-term records (longer than 25 years) are available	Allows for continued analysis of long-term trends in the aquifer

Groundwater Monitoring Wells

Groundwater levels can be measured through a variety of methods. Wells typically are designed to accommodate water level readings as well as water-quality sampling.

Sampling Program

A comprehensive program to monitor groundwater levels requires consideration of the spatial distribution of the wells to be used and the frequency at which these wells will be measured.

Spatial distribution

Water level/quality rounds, or snapshots, provide a concurrent view of the water-table surface/salinity that can be used, for example, to analyze long-term trends and changes in flow directions, and to provide calibration data for groundwater models. Each snapshot should consistently include the same well set. The well set should be well distributed over the complete monitoring area. Wells at high points, intermediate points, and low points in the flow system should be represented in the network. Examples of selected locations of wells in the network include areas at the top of water-table mounds, at intermediate points in the flow system, near discharge areas such as streams and ponds, and areas near municipal water-supply wells.

Frequency

The sampling frequency is determined by the frequency fluctuations of the water table produced by factors such as recharge, withdrawal of water from supply wells, transpiration, tidal effects, and other factors. The frequency of measurements in any monitoring program depends on the observation objectives. Figure 5 compares daily, weekly, and monthly observations for a single well, and the difference in response for three different wells with daily measurements. Well 1, measured daily, is slowly affected by long-term withdrawal, while well 2, which is not affected by pumping, shows seasonal fluctuations that are caused by natural recharge, transpiration from plants, and summer evaporation. Monthly observations in these wells would be adequate. More frequent measurements would be required for an intensive investigation for trends with responses shorter than other annual or longer-term timeframes. The three graphs representing well 3 show the level of detail acquired with increased sampling frequency. In this case, the daily measurements may be justified to capture the weekly fluctuations that occur; the weekly measurements capture only some of these fluctuations. If the longer term, seasonal fluctuations are of primary importance, then in this case, monthly measurements are adequate. At a minimum, for long-term hydrologic monitoring, 12 monthly water-level snapshots should be made to encompass varying hydraulic conditions (such as pre- and post-monsoon periods, and intermediate conditions). If possible, the monthly sampling interval should be similar so that the interval between measurements is close to 30 days. Measurements should be made as close to simultaneously as possible. That is, all measurements should be made over a 1-2 day period with no hydrologic events, such as precipitation, during the measurement period.

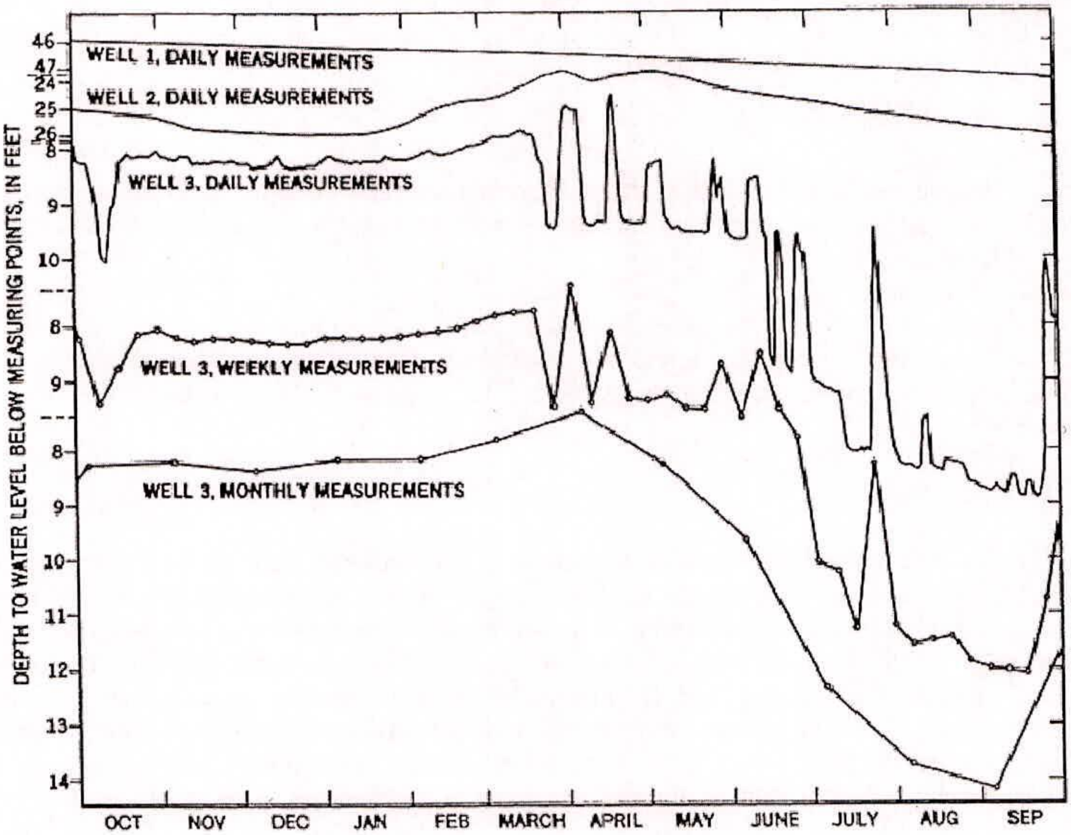

Fig. 5 Graphs showing different types of water-level fluctuations in three observation wells and a comparison between the graphs plotted for daily, weekly, and monthly water levels in the same observation well.

Streamflow

Streamflow monitoring is needed to calibrate and verify groundwater models, to detect change in response to human-induced factors, such as altered land use and groundwater withdrawals, and to provide base-line information for ecosystem health assessment. Streamflow measurements are made periodically to define or verify the stage-discharge relation and to define the time and magnitude of variations in that relation. Effective site selection, correct design and construction, and regular maintenance of both continuous stream-gaging stations and partial-record stream-gaging stations is required for efficient and accurate determination of flow.

Site Selection

The siting of stream-gaging stations is dependent upon the objective of the data-collection effort. Objectives can range from specific water-project monitoring, such as management of a dam, to general hydrologic monitoring in which long-term trends in regional hydrology may be addressed. Regardless of the objective, hydrologic principles must be followed to ensure that optimal information is obtained for the monetary resources spent to operate the data collection station. A fully-instrumented stream-gaging station obtains a continuous record of stage and discharge at the site. In many cases, only intermittent measurements are necessary, and non-continuous, or partial-record stations are sufficient. In either case, the siting criteria are the same. Once the general area or reach of the stream to be measured is determined, specific site considerations can be followed. In general, selected stream-gaging sites should be far enough downstream from hydrologic features that would cause temporal non-uniformity in flow across any part of the width of the stream and far enough upstream from hydrologic features to avoid variable backwater effects. Hydrologic features can include confluence of streams, spillway outlets, and areas of steep streambed-elevation changes. Hydrologic features also can create areas of increased instability in the stream channel; this instability can cause streambed sediment to mobilize and the geometry of the measurement section to change.

Sampling Program

A comprehensive program to monitor streamflow requires consideration of the spatial distribution of the stream reaches to be measured and the temporal frequency at which these stations will be visited.

Spatial Distribution

As per project objectives, the goal of streamflow gaging may be to measure inflow and outflow of surface water to a basin, and the flow of that stream at different water stages. Streamflow monitoring is confined to measurable stream reaches that meet site-selection criteria and, therefore, the spatial frequency of sampling is limited. On the measurable streams, sites are positioned spatially at various reaches of the stream so that sections are evenly distributed. A typical example of a well-distributed stream-station network would include the first station slightly downstream of the stream's origin (such as a pond or lake outlet). Intermediate stations would be set at various sections upstream and downstream of hydrologic features. One final station near the mouth of the stream represents the flow just before discharge out of the stream into another stream, a lake, or the ocean. This distribution provides valuable cumulative data for determination of how each reach contributes (losing or gaining) to total discharge of the stream.

Ponds, Lakes, and Seasonal Wetlands

Lake- and pond-level and quality data provide information that can be used to: (1) calculate surface water body volume for water-supply and ecological studies, (2) create hydrographs that show long-term trends in hydrologic conditions, (3) determine groundwater levels in unconfined systems for water-table mapping, and (4) provide hydrologic information in terms of water quality in areas of critical ecological importance, such as ponds and wetlands.

Site Selection

The surface water body is selected for reasons of location in the flow system, size of the surface water body, ecological importance, and proximity to urban development. Once a water body has been identified for monitoring, the measurement-station site must be selected. An optimal site has easy access, a nearby datum for elevation surveying, low visibility to minimize tampering potential, and a solid structure to support instrumentation such as a staff gage or another type of outside gage.

Pond and Lake Monitoring Devices

Pond and lake-level measurement methods are similar to stage measurements made for stream-gaging purposes. Available monitoring devices for measuring pond, lake, and wetland stages include several designs, such as graduated staff plates (staff gages), pressure transducers in the water body, floats in stilling wells, and a standpipe on the shoreline connected to the water body by a siphon tube.

Sampling Program

A comprehensive program to monitor pond levels requires consideration of the spatial distribution of the ponds in the aquifer to be used and the frequency that these ponds will be measured.

Spatial distribution

The spatial distribution of pond-level measurements is dictated by the pond's locations in the aquifer system. Like sites for groundwater monitoring, ideal pond-level monitoring locations are well distributed and represent most of the network area. Once the measurement network is established, the complete set of pond levels and quality should be measured during each measurement round.

CONCLUDING REMARKS

The scientifically credible and cost-effective monitoring of hydrologic change using a standard data-collection protocol is essential for the effective and sustainable management of coastal zones. Developing and initiating long-term hydrologic monitoring programs can provide a better understanding of effects of natural and human-induced change at both the local and regional scales on coastal groundwater resources and assist the natural resource managers to track changes and assess the impact of management strategies in coastal zones.

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