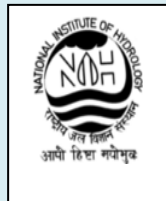


Estimation of Specific Yield and Storage Coefficient of Aquifers

Final Report

(2013-15)



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PREFACE

Specific yield and storage coefficient basically governs the extractable quantity of water from aquifers. Though guiding values of specific yield and storage coefficient are available for various geological formations, but the actual geological formations rarely exist homogeneous and isotropic. Therefore, accurate estimation of specific yield and storage coefficient is very important under the varying range of field conditions and hence requires a skilful effort. In this context, the present study “*Estimation of Specific Yield and Storage Coefficient of Aquifers*” was envisaged to compile various methods and prepare a state-of-the-art report on the estimation of ‘*Specific yield*’ and ‘*Storage coefficient*’. The work encompasses of various methods and techniques for the estimation of specific yield and storage coefficient including their merits and demerits, and also the data requirement of each method. Besides this, a software tool is also developed based on the work carried out under this study. This tool can be used for both estimation of specific yield and storage coefficient and also selection of estimation method(s).

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ABSTRACT

The specific yield and the storage coefficient are the two main parameters that play very vital role in the groundwater estimations. The accuracy of groundwater resource estimation greatly relies on these parameters. Numerous methods are available in literature but the selection of the suitable method and its data requirements under varying range of field conditions is a tedious job. In this context, the present study is proposed to compile various methods and prepare a state-of-the-art report on the estimation of ‘*Specific yield*’ and ‘*Storage coefficient*’.

Keeping the above points in view, the present study entitled “*Estimation of Specific Yield and Storage Coefficient of Aquifers*” has been carried out to find the best possible method(s) under varying range of field conditions. The report presents detailed review of literature on various techniques and methods, their merits and demerits, data requirements of each method, and priority of selection of these methods. A qualitative comparison of various methods is also presented. For numerical computation of specific yield by various methods, an easy-to-use software tool (*SpicY_Est*) is developed which not only helps in deciding the suitable method(s) but also in assessment of their data requirements.

1.0 INTRODUCTION

Water exists on the earth in various forms viz. vapours in the atmosphere, snow and glaciers, lakes and reservoirs, streams and rivers, groundwater and soil moisture, and vegetation and creatures. With the advancement of science and technology, measurement of water in various forms became easier. Precise measurement of water, in present time, has become the necessity because of increasing scarcity of this precious natural resource. The scarcity of water in its fresh form has resulted because of increasing demand in response to growing population, and contamination and pollution of fresh water bodies due to urbanization and industrialization.

Groundwater is the portion of the Earth's water cycle that flows underground. Groundwater originates from precipitation that percolates into the ground through soil and porous/fractured rocks. The water table separates the saturated, or aquifer zone, from the unsaturated, or vadose zone, where the water does not fill all the voids or spaces in the soil or rock. As a general trend, water moves downward in the unsaturated zone joins the water table while in the saturated zone water moves primarily along hydraulic gradients, from higher to lower elevations. The ocean is the natural sink for groundwater flows. In many parts of our country and world, uncontrolled drilling and pumping have led to problems related to scarcity of groundwater, declining groundwater table, deteriorating groundwater quality, failure of wells, etc. to mention a few important ones. Groundwater as a dependable source and its proximity to various users has led to indiscriminate extraction of this precious resource for agricultural, domestic and industrial uses. The development of groundwater resources in depleted areas, therefore, needs to be regulated and augmented through suitable measures to provide sustainability. Since rainfall being the main source of recharge to groundwater, substantial volume of surplus monsoon runoff, which flows out into the sea, has to be conserved and recharged to groundwater reservoir. The benefits will definitely result in terms of rise in water level and consequent increase in the storage of groundwater reservoir.

Groundwater monitoring network is also very necessary for measurement of groundwater levels and its quality besides system parameters. The data monitored under this task can be used for accurate estimation of the availability of groundwater storage, its variation with time both in quantity and quality.

The *specific yield* and the *storage coefficient* are the two main parameters that play very vital role in any groundwater study. The accuracy of various types of groundwater resource estimation

and computation greatly rely on these two parameters. If these parameters bear certain accuracy issues in themselves, the accuracy of groundwater estimations would be largely influenced. In country like ours, groundwater plays a vital role for uses in all water demanding sectors. Therefore, get to know about the advancement in accurate estimation of these parameters has always been a demanding subject. Numerous methods are available in literature for the estimation of ‘specific yield’ and ‘storage coefficient’ but the selection of the best suitable method and data requirements is again a tedious job. In this context, the present work has been carry out to find options and suitability of methods under varying site conditions for the estimation of specific yield and storage coefficient. The proposed technical document will help researchers and groundwater professions to have compiled information and data at one place.

1.1 Specific Yield

Specific yield (S_y), which is also known as drainable porosity, is the volume of water released from storage by an unconfined aquifer per unit surface area of the aquifer per unit decline of the water table. Specific yield tells how much water is available for use. It is expressed either as a ratio or as a percentage of the volume of the aquifer as follows:

$$S_y = \frac{V_d}{V_t} \quad \dots \quad (1)$$

where V_d is the volume of water that drains from a total volume of V_t .

Hydrologists divide the water stored in the ground into the part that will drain under the influence of gravity (called *specific yield*) and the part that is retained as a film on rock or soil surfaces and in very small openings (called *specific retention*).

Meinzer (1923a) defined the specific yield of a rock or soil, with respect to water, as the ratio of the volume of water which, after being saturated, it will yield by gravity to its own volume. This ratio usually is expressed as a percentage. Because it represents the void space that will yield water to wells and is therefore effective in furnishing water supplies, thus specific yield occasionally is also known as *effective porosity*. However, because of confusion with similar terms with slightly different meanings used by soil scientists who also occasionally call it *non-capillary porosity* and petroleum geologists prefer the term *specific yield*.

Meinzer (1923b) further indicated that the distinction between gravity water and retained water is not definitive, because the quantity of water that will drain from a rock or soil material

depends on the length of time the rock or soil is allowed to drain, on the temperature and the mineral composition of the water, both of which affect its surface tension, viscosity, and specific gravity and on various physical characteristics of the rock or the soil under consideration.

1.2 Storage Coefficient

Storativity or storage coefficient (S) is the volume of water released from storage per unit area of the aquifer per unit decline in hydraulic head in the confined aquifer. In a confined aquifer (or aquitard), storativity is defined as:

$$S = S_s \cdot B \quad \dots \quad (2)$$

where S is the storativity, S_s is the specific storage and B is the aquifer (or aquitard) thickness.

For a confined aquifer, the specific storage is mathematically represented as

$$S_s = \gamma(n\beta + \alpha) \quad \dots \quad (3)$$

where $\gamma = \rho g$ = unit weight of water, n = porosity of the aquifer, β = compressibility of water, and α = compressibility of the pores. The unit of specific storage is $[L^{-1}]$. The specific storage represents the volume of water released from storage from a unit volume of aquifer due to a unit decrease in the piezometric head. The numerical value of the specific storage is very small of the order of $1 \times 10^{-4} m^{-1}$.

For an unconfined aquifer, the storage coefficient (S) is mathematically represented as

$$S = S_y + \gamma(n\beta + \alpha) \cdot B_s \quad \dots \quad (4)$$

where B_s = saturated thickness of the aquifer. The second term of this equation is very small as compared to S_y . Thus the storage coefficient of unconfined aquifers is almost same as the specific yield.

For highly permeable fractures, storativity (S) should be the sum of the storage coefficient (S) of the fractured rock aquifer and the specific yield (S_y) of the fracture and is expressed as

$$S = S_y + S_c$$

Woodford (2002) stated that storativity of a fracture in a pumping process is complex and varies spatially and temporally.

1.3 Aquifer Storage

Basically, the potential water storage in a saturated aquifer is equal to the total porosity of the aquifer. This potential water storage is the maximum capacity of the aquifer to hold water. This capacity includes both drainable water (called specific yield) as well as retention water (called specific retention). The porosity of an aquifer medium is thus defined by ASTM (1961) as the ratio of volume of voids of a given rock or soil mass to the total volume of the rock or soil mass. Mathematically, it can be defined as

$$\phi = \frac{V_v}{V} \quad \dots \quad (5)$$

where, V_v = the volume of voids in a given rock or soil mass, and V = the total volume of the rock or soil mass. The porosity is a measure of the quantity of water per unit volume. In terms of specific yield and specific retention, it can be expressed as

$$\phi = S_y + S_r, \text{ dimensionless} \quad \dots \quad (6)$$

where S_y = the specific yield which represents the actual volume of water that can be extracted by the force of gravity, and S_r = the specific retention which represents the fraction of water held back in an aquifer against the force of gravity. For any medium, if S_y is more, S_r will be less and *vice-versa*.

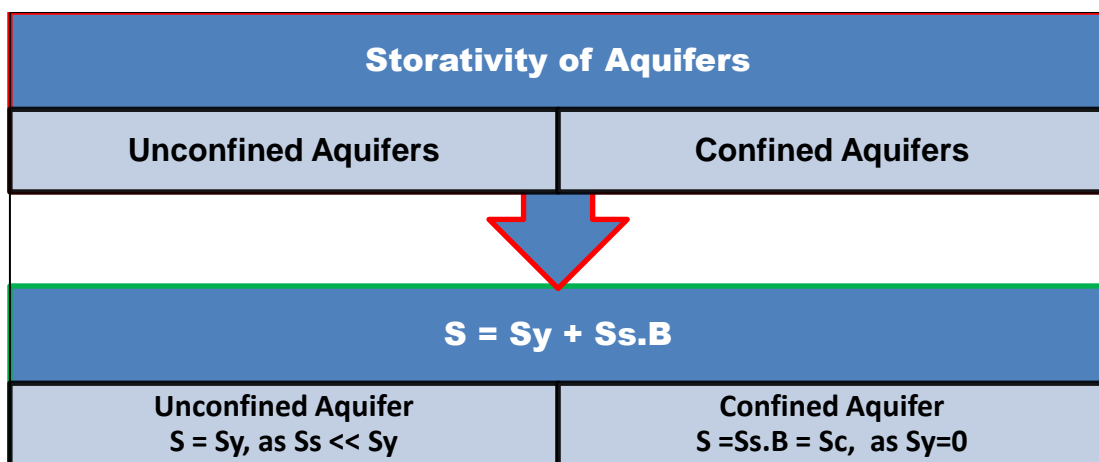


Figure 1. Schematic showing specific yield of confined and unconfined aquifers

Thus the total aquifer storage depends on the porosity of the aquifer material while its utilizable storage depends on the specific yield and can be expressed as:

$$\textit{Total Aquifer Storage} = f(\phi)$$

$$\textit{Utilizable Aquifer Storage} = f(S_y)$$

If one wants to know the volume of water (V) that will be drained from or added to an aquifer as the head is raised or lowered, the equation for calculation of volume is:

$$V = S \cdot A \cdot \Delta h \quad \dots \quad (7)$$

where S is the storage coefficient, A is the area overlying the aquifer, and Δh is the head raised or lowered. This equation is primarily followed for estimation of potential groundwater resources in India. Groundwater Estimation Committee (GEC-1984, 1997 and 2004) suggested the following norms for estimation of groundwater recharge:

- (i) Groundwater table fluctuation and Specific yield method.
- (ii) Rainfall infiltration method.

Between the above two methods, '*Groundwater table fluctuation and Specific yield method*' is mostly preferred. The change in groundwater storage volume during pre- and post-monsoon that appears in the estimation of recharge component is calculated using equation (7). While all other variables of equation (7) except specific yield value can explicitly be measured from field observation but the estimation of specific yield in the zone of water table fluctuation, although suggested for computation from pumping tests, is the primary crux of getting reasonable accuracy in the estimate of storage volume. There are guiding values of S_y for different geological formations, but the actual geological formations are rarely found homogeneous and isotropic, mostly heterogeneous and anisotropic. Therefore, selection of appropriate S_y value requires a skilful effort.

There are numerous approaches for estimation of specific yield; these approaches involve laboratory and field based estimation methods. Over the years, researchers have carried out a number of studies and suggested different methods for estimation of specific yield, in the zone of water table fluctuation, and storage coefficient.

Thus, the study has been proposed with the following objectives:

1. Compilation and critical appraisal on various methods developed and widely used for estimation of specific yield and storage coefficient.
2. Preparation of a state-of-the-art report on estimation of specific yield and storage coefficient.

1.4 Issues related to the Specific Yield and Storage Coefficient

There are following issues that need to address while selecting or determining the specific yield and storage coefficient value:

- Heterogeneity of aquifer formation
- Horizontal scale of assessment
- Vertical scale of assessment
- Aquifer type and conditions

Because of the heterogeneity of the aquifer material, the specific yield and storage coefficient vary from point to point or place to place. Considering an average value for a sufficient size area may result in large variations in the groundwater resource estimations. Similar is the case with horizontal scale of determination of specific yield/ storage coefficient. The groundwater is dynamic in nature and its assessment, variation, draft and movement is linked to the spatial scale. If the scale of determining method is site-specific, it needs a number of data points. If the scale is unit area, then it seems a good estimate of the specific yield/storage coefficient for that area. As mentioned above, that the storage coefficient also depends on compressibility of pores as well as of water, weight of overburden material also has significant impact on the yield capacity of aquifers. If the aquifer material is less compressed, it will hold more water and *vice-versa*. Thus it becomes important to consider the vertical scale also while determining the storage coefficient. The aquifer type and its formations also have large impact on the specific yield/storage coefficient. Whether the aquifer is confined or unconfined, alluvial or fractured, density of fractures, shallow or deep, etc will help in determining the suitable method for the specific yield/storage coefficient.

2.0 REVIEW OF LITERATURE

A comprehensive review on specific yield and storage coefficient and its estimation has been done and is presented below:

Specific yield (S_y) as defined above is the volume of water released from storage by an unconfined aquifer per unit surface area of aquifer per unit decline of the water table. Table 1(a) and (b) show the representative values of specific yield for various geologic materials.

The storativity (S) of a confined aquifer (or aquitard) as already defined above is the volume of water released from storage per unit surface area of a confined aquifer (or aquitard) per unit decline in hydraulic head. Storativity generally ranges between 0.00005 and 0.005 in confined aquifers. The storage coefficient and specific storage are related to the compressibility of the aquifer (or aquitard) as given by equations (3) and (4). Table 2 shows representative values of specific storage for various geologic materials (Batu, 1998).

Table 1(a). Representative values of specific yield for various geologic materials (Morris and Johnson, 1967)

Material	Specific Yield (%)
Gravel, coarse	21
Gravel, medium	24
Gravel, fine	28
Sand, coarse	30
Sand, medium	32
Sand, fine	33
Silt	20
Clay	6
Sandstone, fine grained	21
Sandstone, medium grained	27
Limestone	14
Dune sand	38
Loess	18
Peat	44

Schist	26
Siltstone	12
Till, predominantly silt	6
Till, predominantly sand	16
Till, predominantly gravel	16
Tuff	21

Table 1(b). Specific yield norms for estimation of recharge (MoWR, 2009)

Region	Formation	Recommended Value (%)	Minimum Value (%)	Maximum Value (%)
Alluvial Areas	Sandy alluvium	16.0	12.0	20.0
	Silty alluvium	10.0	8.0	12.0
	Clayey alluvium	6.0	4.0	8.0
Hard Rock Areas	Weathered granite, gneiss and schist with low clay content	3.0	2.0	4.0
	Weathered granite, gneiss and schist with significant clay content	1.5	1.0	2.0
	Weathered or vesicular, jointed basalt	2.0	1.0	3.0
	Laterite	2.5	2.0	3.0
	Sandstone	3.0	1.0	5.0
	Quartzite	1.5	1.0	2.0
	Limestone	2.0	1.0	3.0
	Karstified limestone	8.0	5.0	15.0
	Phyllites, Shales	1.5	1.0	2.0
Massive poorly fractured rock	0.3	0.2	0.5	

Note:- Usually the recommended values should be used for assessment, unless sufficient data based on field study is available to justify the minimum, maximum or other intermediate values.

Table 2. Representative values of specific storage for various geologic materials

Material	Specific Storage (ft⁻¹)
Plastic clay	7.8×10^{-4} to 6.2×10^{-3}
Stiff clay	3.9×10^{-4} to 7.8×10^{-4}
Medium hard clay	2.8×10^{-4} to 3.9×10^{-4}
Loose sand	1.5×10^{-4} to 3.1×10^{-4}
Dense sand	3.9×10^{-5} to 6.2×10^{-5}
Dense sandy gravel	1.5×10^{-5} to 3.1×10^{-5}
Rock, fissured	1×10^{-6} to 2.1×10^{-5}
Rock, sound	$< 1 \times 10^{-6}$

The most widely used procedure for determining specific yield involves the selection of a value that causes a mathematical solution of the Boussinesq equation to most nearly agree with a corresponding set of data. The familiar constant-rate pumping test is the most common, although other flow situations have been used, particularly in agricultural drainage applications (van Schilfgarde, 1974).

McWhorter (1984) stated that the relation between the volume of water removed and the associated drawdown is quantified by the storage coefficient in the case of artesian conditions and by the specific yield in case of unconfined aquifers. Field aquifer tests, performed by pumping and observing the corresponding drawdown, are the most reliable methods for estimation of these two important hydrologic parameters. However, field aquifer tests for the estimation of specific yield are applicable only if the aquifer is unconfined. Thus to estimate the quantity of water ultimately recoverable from an artesian aquifer, methods other than the traditional aquifer test must be utilized to estimate the specific yield. Because the volume of recoverable water is comprised almost entirely of water recovered under unconfined conditions, any uncertainty in the estimate of specific yield is directly reflected as a corresponding uncertainty in the estimated recoverable volume. Even small differences between independent estimates of specific yield can represent large differences in estimated recoverable volumes with attendant important economic ramifications.

The specific yield can also be calculated from moisture retention data (McWhorter, 1984). This is conveniently accomplished by calculating the change in the unit area volume of air associated with a decline of the water table.

The specific yield can also be estimated from the texture of the aquifer material (Davis and De Wiest, 1966). When the water table is near the soil surface (e.g. within 2 m of the soil surface), the specific yield of the soil layers near the surface need to be determined. The specific yield of shallow soil layers can be determined either from a field experiment or from a lysimeter experiment (Prathapar and Sides, 1993).

The storativity of fractured rock aquifer is scale-dependent (Jia, 2007). On a microscopic scale, the storativity can be estimated by core sample porosity, which accounts for the storativity of both fractures and matrix rocks at scale of less than one meter. On a mesoscopic scale or a site scale, storativity values are usually derived from pumping test analyses. Under a steady flow condition, the storativity values derive from pumping tests may account for the aquifer porosity at a scale of several meters to hundred meters. However groundwater flow in the fractured rock is mostly controlled by the characteristics of fractures, such as orientation, density, aperture, and connectivity.

The total porosity of basaltic rocks is controlled by void spaces in the rock, vesicles, cracks, separations at contacts between flows, and lava tubes (Oki, 2005). However, effective porosity may be up to an order of magnitude lower because not all existing pores are hydraulically interconnected and provide a pathway for ground-water flow (Oki, 2005). The advantage of step-drawdown tests is that they provide a direct estimate of hydraulic conductivity, thereby avoiding uncertainties related to aquifers thickness. Furthermore, the analysis of step-drawdown tests includes a correction for well loss, which makes it suitable for aquifer test without an observation well. Other advantages are that step-drawdown tests are faster to complete than constant rate tests.

Marechal (2006) developed a water budget approach to jointly estimate specific yield and natural recharge in an unconfined aquifer with significant seasonal water table fluctuations. The advantage of the proposed method is that specific yield and recharge are estimated at the scale of interest to basin hydrologic studies and that the method requires no extensive in situ instrumentation network. This methodology enables to overcome the main limitation of the classical Water Table Fluctuation (WTF) technique, i.e. unknown specific yield, by determining it at the suitable watershed scale and within an acceptable range of uncertainty according to the available observation

network. Obviously, the accuracy of the technique increases with the number of measurements on the water table. Therefore, this technique is well suited to developing countries and semiarid areas, where the presence of many agricultural dug wells and bore wells throughout a basin provides a high-density observation network. For economic reasons, it is important to optimize the amount of piezometric data needed to guarantee an acceptable accuracy in the application of this methodology.

Meinzer (1923a) pointed out that methods for determining specific yield have been so little standardized that specific-yield data always should be accompanied by a statement of the methods used, especially as to size of sample and period of draining.

Johnson (1963) pointed out that the quantity of water yielded to wells from a body of saturated rock or soil depends upon its specific yield and not upon its porosity. As an example, the specific yield is 8 percent if a volume of saturated rock 10 feet thick and 100 feet square (100,000 cu ft) will supply 60,000 gallons (8,000 cu ft) of water when drained by pumping from well so if the rock still retains a total of 13,000 cu ft of water in its void spaces after drainage, its specific retention would be 13 percent and its porosity would be 21 percent (8 + 13). Certain materials, such as clay, have high porosities and, thus, are capable of holding large quantities of water but yield only a small part of it in a reasonable length of time; consequently these materials usually are worthless as aquifers.

Johnson (1963) stated that although most field methods determine specific yield directly, most laboratory methods determine specific retention, and specific yield is found indirectly by subtracting the specific retention from the porosity.

Johnson (1963) also reported that the specific yield varies depending on the interrelation of textures; for example, a silt over a sand may not have as high a specific yield as would the same silt over a clay.

Todd (1959) stated that all methods of specific yield determination have limitations - laboratory samples may be disturbed or not representative, it is difficult to control and measure variables in field tests, and estimates often lack accuracy.

Tolman (1937) noted that "perhaps the greatest difficulty in the application of quantitative methods lies in the variability in the texture and hence in the hydrologic properties of the water-bearing materials. The hydrologic properties vary greatly, even with apparently slight differences in

texture. Hence the ordinary geologic descriptions are quite inadequate for hydrologic purposes, and quantitative descriptions based on laboratory determinations have become essential.

Robson (1993) mentioned that the specific yield is typically about 1,000 times larger than storage coefficient for most aquifers so the volume of water released from elastic storage usually is negligibly small in comparison to the volume released from gravity drainage.

Robson (1993) described that in drainage experiments, equilibrium is difficult to achieve because of the incomplete drainage of heterogeneous aquifer materials and the slow drainage of the unsaturated zone, particularly in fine-grained materials. As a result, specific yield calculated from field-drainage experiments of limited duration (such as aquifer tests) usually is smaller than the true specific yield of the aquifer material. Specific yields determined through use of centrifuge or porous-plate laboratory techniques have been shown (Neuman, 1987) to be less affected by slow drainage and, thus, are better indicators of the equilibrium specific yield of aquifer materials.

Bolster et al. (2001) used data from a large-scale canal-drawdown test to estimate the specific yield of the Biscayne Aquifer, an unconfined limestone aquifer in southeast Florida. The drawdown test involved dropping the water level in a canal by about 30 cm and monitoring the response of hydraulic head in the surrounding aquifer. Specific yield was determined by analyzing data from the unsteady portion of the drawdown test using an analytical stream-aquifer interaction model (Zlotnik and Huang, 1999). Specific yield values computed from drawdown at individual piezometers ranged from 0.050 to 0.57, most likely indicating heterogeneity of specific yield within the aquifer (small-scale variation in hydraulic conductivity may also have contributed to the differences in specific yield among piezometers). A value of 0.15 (our best estimate) was computed based on all drawdown data from all piezometers.

Gehman et al. (2009) conducted two high-precision gravity surveys to determine groundwater mass changes at a managed groundwater recharge site in northeastern Colorado. Inverse modeling of the gravity data indicated a $5.1 \times 10^5 \text{ m}^3$ decrease in storage beneath the recharge ponds between the two surveys, which we attribute to dissipation of the groundwater mound created by recharge during pumping. This estimate of the change in groundwater storage is made independently of assumptions of physical properties of the aquifer. Dividing the change in water volume per unit area determined from the gravity modeling by the change in water level measured in wells provides an estimate of specific yield of 0.21 ± 0.03 , which is within the range of specific yield estimates derived from aquifer tests at the site.

Shah and Ross (2009) carried out investigations concerning the variable behavior of specific yield under shallow water table conditions (<2 m below land surface). It is often used as a fixed value in groundwater flow models. This study presents specific yield variability due to natural processes of evapotranspiration and recharge. HYDRUS 1D - a numerical model solving Richard's equation for saturated-unsaturated flow in one dimension is used to simulate the behavior of specific yield for a soil type representative of west central Florida. It was found, that for various cases examined (e.g., ET and infiltration), the magnitude of specific yield varied with depth to water table. For infiltration response, the variation in the specific yield exhibited strong dependence on the inter-event time. For ET stress, the specific yield first increased rapidly to attain a maximum value and then declined steadily to ultimately become less than specific yield at equilibrium moisture conditions. The study indicated that assumptions of constant specific yield for different stresses can yield erroneous results especially in shallow water table environments. For deeper water table it was found that variation was not that pronounced and a constant value of specific yield can be used as an approximate value for simulating water table fluctuations.

Bateni et al. (2015) stated that in-situ measurements of aquifer hydraulic parameters are expensive and difficult. Traditionally, these parameters have been estimated by graphical methods that are approximate and time-consuming. In this study, Genetic Algorithm (GA) and Ant Colony Optimization (ACO) methods are used to identify hydraulic parameters (i.e., storage coefficient, hydraulic conductivity, transmissivity, specific yield, and leakage factor) of three types of aquifers namely, confined, unconfined, and leaky from real time-drawdown pumping test data. The performance of GA and ACO is also compared with that of graphical and NLP techniques. The results show that both GA and ACO are efficient, robust, and reliable for estimating various aquifer hydraulic parameters from the time-drawdown data and perform better than the graphical and NLP techniques.

Cheng et al. (2015) presented a new expression to describe the relationship between the specific yield under steady-state condition and shallow groundwater drainage. The expression is based on the relationship between soil water content-soil depths below ground surface near the saturation zone, i.e. water content profile, which can be fitted by the van Genuchten model. Compared with the expression obtained from the Brooks-Corey model, the new expression can be used for a variety of aquifer and soil media. The improved accuracy of the specific yield provides a better estimate of discharge rates in shallow groundwater systems with water table fluctuations.

3.0 MATERIAL AND METHODS

The underground formations are highly heterogeneous in nature and pose difficulty in deciding the system parameters. As a result, there are more chances of uncertainties in the water resource estimations. The present study, therefore, focuses on compilation on various techniques and methods, their merits and demerits, data requirements of each method, and priority on selection of these methods including a qualitative comparison of various methods. For numerical computation and selection of these methods for estimation of specific yield and storage coefficient, an easy-to-use software tool, named *SpicY_Est*, is developed. A *user's manual* is also prepared for supporting the easy operation of the developed software.

The software has the following capabilities:-

- i. selection of methods for estimation of specific yield based on:
 - (a) formation type, and
 - (b) availability of data,
- ii. assessment on data requirements of selected method(s),
- iii. estimation of specific yield by numerous methods,
- iv. getting the tabular or graphical values of specific yield.

In addition to above, this may also be used to compute aquifer parameters using drawdown test in unconfined and confined aquifers and recovery test in confined aquifer using the most common methods.

The determination of storage coefficient and specific yield comprises of various methods that include field measurements, laboratory analysis of undisturbed core samples, estimation methods, and inverse modeling techniques. Descriptive details on all these methods and techniques have been given in the following sections:

3.1 Methods for the Estimation of Specific Yield

The methods for the estimation of specific yield can be categorized as shown in Figure 2.

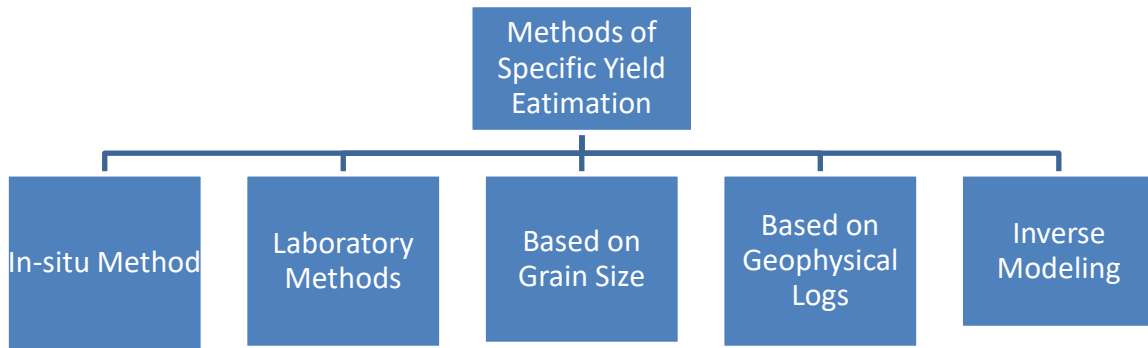


Figure 2. Schematic showing various methods for the estimation of specific yield

3.1.1 Based on Field Measurements

The most common method of specific yield measurement in field is the pump-test method. The aquifer test method should be selected on the basis of (i) the hydrogeology of the test site, (ii) the field test conditions. Additional set of criteria that affects the method selected often involves the available budget, the project timeline, and the consequences of the results on future work. The hydrogeology of the test site (such as confined, unconfined, leaky confined or non-leaky confined, and other natural conditions of the site) helps to determine the applicable set of aquifer-test methods. Other parameters that support the selection of aquifer-test method include number and location of observation wells, if any, the instrumentation for measuring water level, and the screened interval of the well and the well capacity of the pump.

3.1.1.2 Measurement of Specific Yield

Specific yield is measured by a variety of techniques that involve laboratory measurement, field methods, and estimation techniques. Among these techniques and methods, well pumping tests, in general are believed to give the most reliable results from the field measurement techniques.

3.1.1.2.1 Pump Tests

An aquifer pump test is conducted to evaluate the response of an aquifer (called drawdown) in an observation well as a result of groundwater pumping. On the other hand, a slug test is a variation on the typical aquifer test where an instantaneous change (increase or decrease) is made,

and the effects (groundwater level change) are observed in the same well. This is often used to get a quick estimate (minutes instead of days) of the aquifer properties immediately around the well.

The aquifer properties can be estimated by pump-test data using a variety of analytical solutions involving different conceptualizations and simplifying assumptions. These analytical solutions are impacted by their simplifying assumptions, which limit their applicability to characterize certain types of unconfined aquifers. Under field conditions in unconfined aquifers, specific yield can be determined by various methods as given in Table 3. The descriptive details of these methods are available in standard text books.

Table 3. Various methods used for the determination of specific yield

S.N.	Type of Aquifer	Methods
Pump-Test Solutions (Constant or variable pumping rates)		
1	Unconfined	Theis (1935)
2	Unconfined	Cooper-Jacob (1946)
3	Unconfined	Neuman (1974)
4	Unconfined	Moench (1997)
5	Unconfined	Tartakovsky-Neuman (2007)

Limitation of Various Methods

- All solutions since Boulton (1954a) assume the water table is fixed horizontal $\xi(r, t) = h_0$ during the entire test, even close to the pumping well where large drawdown is often observed.
- Well test solutions suffer from the complication related to the unknown distribution of flux across the well screen. Commonly, the flux distribution is simply assumed constant, but it is known that flux will be higher near the ends of the screened interval that are not coincident with the aquifer boundaries.
- In real-world tests, heterogeneity is present at multiple scales. Large-scale heterogeneity (e.g., faults or rivers) can sometimes be accounted in analytical solutions using the method of images, or other types of superposition. A stochastic approach could alternatively be developed to estimate random unconfined aquifer parameter distribution parameters (Neuman et al., 2004).

Bolster et al. (2001) estimated the specific yield using the drawdown test that involved dropping the water level in a canal by about 30 cm and monitoring the response of hydraulic head in the surrounding aquifer. The specific yield was then determined for the unsteady portion of the

drawdown test using an analytical stream-aquifer interaction model (Zlotnik and Huang 1999). The values of specific yield at individual piezometers ranged from 0.050 to 0.57, most likely indicating heterogeneity of specific yield within the aquifer (small-scale variation in hydraulic conductivity may also have contributed to the differences in specific yield among piezometers). An average value of 0.15 was computed based on all drawdown data from all piezometers. The specific yield was then incorporated into a large-scale two-dimensional numerical MODFLOW-based ground water flow model for predictions of head during a 183-day period at four wells located 337 to 2546 m from the canal and found good agreement between observed and predicted heads.

Skaggs et al. (1978) used the difference between the volume of soil moisture (an integral of soil water content over a certain depth interval) at two different water-table positions, to calculate specific yield for that change in water level. This can be expressed as:

$$S_y = V_d|_{(y_1+\Delta y)} - V_d|_{(y_1)} \quad \dots \quad (8)$$

where S_y = Specific yield, y_1 = initial depth of water table, V_d = volume of soil moisture (volumetric water content, $m^3 m^{-3}$), Δy = change in water-table position.

3.1.1.2.2 Field Saturation and Drainage

This method is similar in principle to the laboratory method. Meinzer (1932) indicated that a plot of land should be selected where the water table and capillary fringe are at sufficient depth below the surface to permit gravity drainage. The material underlying the plot should then be thoroughly wetted and allowed to drain. Due care shall be taken to avoid all possible evaporation. After a sufficient period of drainage, samples are taken for determination of moisture content (m.c.) and porosity (ϕ), and the specific yield is computed as the difference between these two.

$$S_y = \phi - m.c. \quad \dots \quad (9)$$

3.1.1.2.3 Pumping Method

This method consists of observing the lowering of the water table and determining the volume of sediments drained by pumping a measured volume of water. The specific yield is then obtained as the ratio of the volume of water pumped to the volume of sediments drained (Meinzer, 1932).

$$S_y = \frac{\text{Volume of Water Pumped}}{\text{Volume of Sediments Drained}}$$

3.1.1.2.4 Recharge Method

The recharge method is the converse of the pumping method and consists of observing seepage losses from streams or canals, or the amount of water recharged into an aquifer through a recharge well, and making corresponding observations on the resulting rise of the water table. From these observations the volume of sediments saturated by the measured recharge is determined, and the specific yield can be computed (Meinzer, 1932).

$$S_y = \frac{\text{Volume of Water Recharged}}{\text{Volume of Sediments Saturated}}$$

3.1.1.3 Measurement of Storage Coefficient

3.1.1.3.1 Pump Tests

Under artesian conditions, when the piezometric surface is lowered by pumping, water is derived from storage by the compaction of the aquifer and its associated beds and by expansion of the water itself, while the interstices remain saturated. In confined aquifers, utilizable water is governed by the storage coefficient which is highly dependent on the compressibility of pores which is again dependent on the hydraulic head in the confined aquifer and the overburden soil or rock material. This is why the storage coefficient can best be determined by the pump-test methods where all local conditions like compressibility of pores, pressure head and saturated thickness of aquifer are taken care. Lab and sampling techniques will not work correctly due to lack of effect of local conditions.

Storage coefficient can best be determined from pump tests of wells, or from groundwater level fluctuations in response to atmospheric pressure or ocean tide variations. In the actual field conditions, storage coefficient can be determined by a wide range of methods in different types of aquifers as given in Table 4. Most of these methods yield storativity of the aquifer while some of them yield specific storage, from which storativity value can be obtained. The descriptive details of these methods are available in standard text books.

Table 4. Various methods used for the determination of storage coefficient

S.N.	Type of Aquifer	Methods
Pump-Test Solutions (Constant or variable pumping rates)		
1	Confined	Theis (1935)/Hantush (1961)
2	Confined	Theis (1935) residual drawdown/recovery
3	Confined	Theis (1935) step-drawdown test
4	Confined	Cooper-Jacob (1946)
5	Confined	Moench-Prickett (1972) unconfined conversion
6	Confined	Papadopulos-Cooper (1967)
7	Confined	Dougherty-Babu (1984)
8	Confined	Dougherty-Babu (1984) step-drawdown test
9	Confined	Hantush (1962) wedge-shaped aquifer
10	Confined	Murdoch (1994) trench
11	Confined	Daviau et al. (1985) uniform-flux horizontal well
12	Confined	Daviau et al. (1985) infinite-conductivity horizontal well
13	Confined	Barker (1988)
14	Leaky	Hantush-Jacob (1955)/Hantush (1964) without aquitard storage
15	Leaky	Hantush-Jacob (1955) step-drawdown test
16	Leaky	Hantush (1960) with aquitard storage
17	Leaky	Hantush (1960) early-time solution
18	Leaky	Cooley-Case (1973) water-table aquitard
19	Leaky	Neuman-Witherspoon (1969) confined two-aquifer system
20	Leaky	Moench (1985) Case 1: constant head
21	Leaky	Moench (1985) Case 2: no-flow
22	Leaky	Moench (1985) Case 3: both
23	Fractured	Moench (1984) slab-shaped blocks
24	Fractured	Moench (1984) spherical blocks
25	Fractured	Barker (1988) slab-shaped blocks
26	Fractured	Barker (1988) spherical blocks
27	Fractured	Gringarten-Witherspoon (1972) uniformflux vertical fracture
28	Fractured	Gringarten et al. (1974) infinite-conductivity vertical fracture
29	Fractured	Gringarten-Ramey (1974) uniform-flux horizontal fracture
Slug-Test Solutions		
1	Confined	Cooper-Bredehoeft-Papadopulos (1967)
2	Confined	Dougherty-Babu (1984)
3	Confined	Hyder et al. (1994), i.e., KGS Model (1994)
4	Confined	Butler-Zhan (2004) inertial
5	Confined	Peres et al. (1989) deconvolution
6	Unconfined	Hyder et al. (1994), i.e., KGS Model (1994)
7	Fractured	Barker-Black (1983)

Constant Head (Pump Tests) Solutions		
1	Confined	Jacob-Lohman (1952)
2	Confined	Hurst-Clark-Brauer (1969)
3	Confined	Dougherty-Babu (1984)
4	Confined	Barker (1988)
5	Leaky	Hantush (1959)
6	Leaky	Moench (1985) Case 1: constant head
7	Fractured	Barker (1988) slab-shaped blocks
8	Fractured	Barker (1988) spherical blocks
9	Fractured	Ozkan-Raghavan (1991) uniform-flux vertical fracture
10	Fractured	Ozkan-Raghavan (1991) infinite-conductivity vertical fracture

3.1.2 Based on Laboratory Analysis

Under the laboratory methods, specific yield is estimated using the following equation

$$S_y = \phi - SR \quad \dots \quad (10)$$

where, ϕ = the porosity, and SR = the specific retention.

In equation (10), both porosity and specific retention are determined separately from the undisturbed core samples using the laboratory methods. Porosity can be determined in laboratory by use of a helium gas-expansion porosimeter and a mercury-immersion displacement porometer, and the specific retention can be calculated from the moisture-retention data.

3.1.2.1 Sample Saturation and Drainage

The method of sample saturation and drainage consists of draining columns of saturated materials by gravity and determining both the volume of material drained and the volume of water yielded. The volume of water yielded can be measured directly or can be computed from the porosity and the moisture content after draining, but the columns must be long enough to avoid having an undue percentage of the column occupied by the capillary fringe. Meinzer (1932) pointed out that care must be taken to prevent loss by evaporation and the tests must be made at a uniform temperature or corrections for temperature variations must be applied. Because drainage continues for a long time at a diminishing rate, Meinzer (1932) also noted that the specific yield should be determined for specified periods of drainage.

King (1899) published results of tests of the water-yielding and water-retaining capacities of assorted sands of five different sizes of particle, when these sands were saturated and then allowed to drain over a long period of time. Five galvanized-iron cylinders, 8 feet long and 5 inches in diameter, were filled with sand, and water was introduced at the bottom until the sand was saturated. The columns were allowed to drain for a period of 2.5 years. Discharged water was measured or weighed at frequent intervals initially and later only every few days, weeks, or months. At the conclusion of the tests, the quantity of water remaining in each 3-inch layer of sand was determined. The results of King's tests showed discrepancies of about 5 to 7 % between the porosity (representing the total water content possible under saturated conditions) and the total quantity of water accounted for. King's tests seemed to give lower-values for specific retention than Hazen's tests, especially for the coarser samples.

3.1.2.2 Correlation with Particle Size

Particle-size analysis may be considered a method of estimating specific yield. By determining the specific retention by some other method and the effective size or median diameter by particle-size analysis, the relation of the two could be graphically represented by a curve (Meinzer, 1923b). By determining the effective size or median diameter of a sample and referring to the curve, the approximate specific retention could be obtained. After determining the porosity, the specific yield could be obtained as mentioned before. Probably, at best, this method represents a speedy but approximate means for estimating specific yield.

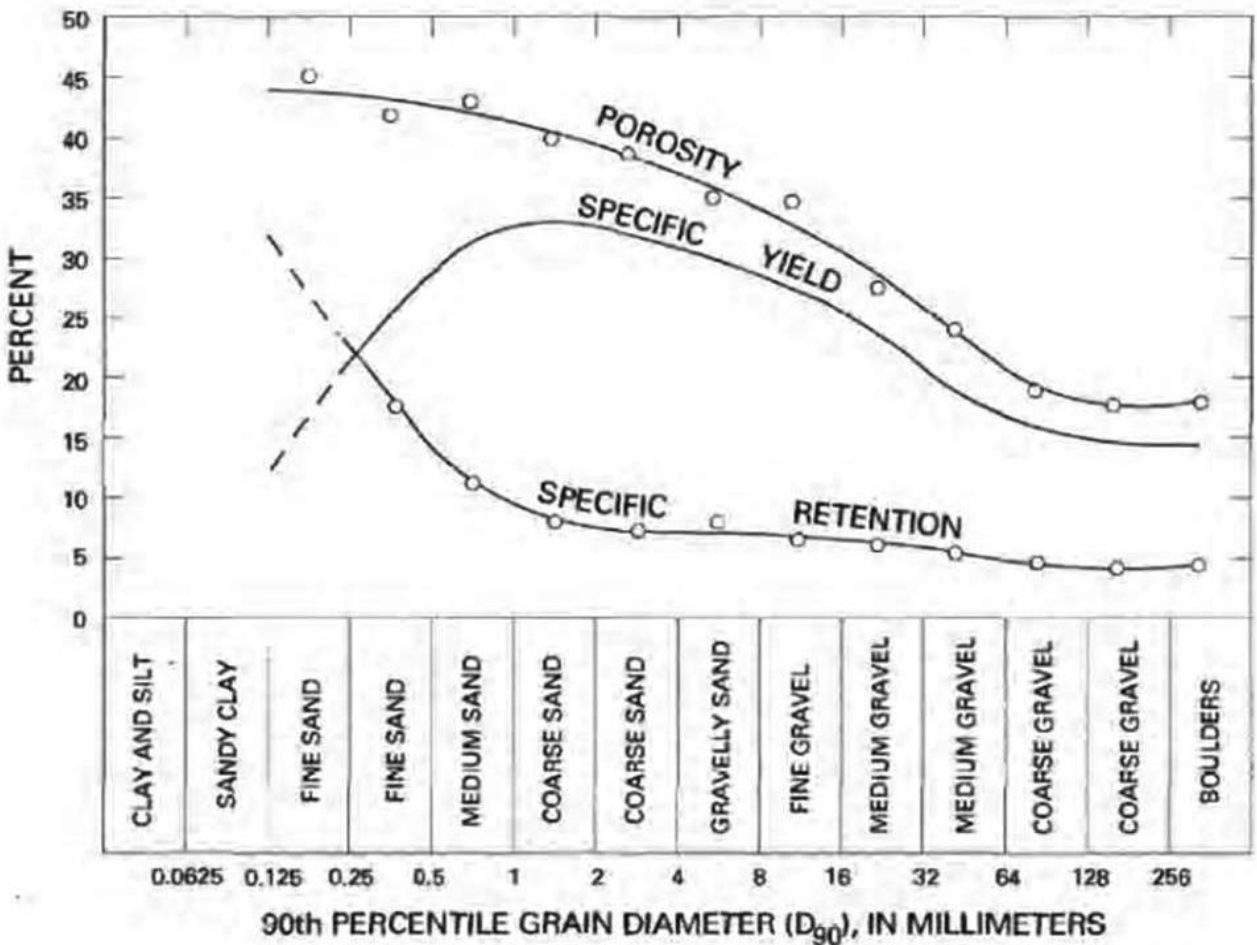
3.1.3 Based on Estimation Techniques

Under the estimation techniques, specific yield can be determined on the basis of various field data like groundwater level, grain-size, geophysical logs, etc.

3.1.3.1 Based on Grain-Size

Under these techniques, specific yield is estimated by use of equation (10) in which mean porosity and specific retention are calculated from the three specimens of the grain-size analysis for each sample (D_{50} , D_{70} and D_{90}). The grain-size data can be obtained from mechanical sieve analyses. Linear relationships may also be developed between the specific retention and the grain-size distribution to estimate the specific retention.

The general relationship among the specific yield, specific retention, and grain-size characteristics of aquifer materials has been reported by many investigators (Meinzer, 1923; Eckis, 1934; Preuss and Todd, 1963; Johnson, 1967) as shown in Figure 3. These relations are merely informative but generally do not yield accurate estimation of specific yield or specific retention from grain-size data because of the large variance in data relating grain size to specific yield and specific retention. Some of the variance can be attributed to non-standardized or antiquated laboratory procedures for measuring specific yield and porosity, such as testing of disturbed and repacked aquifer materials, use of column drainage techniques that cannot accurately measure specific yield of heterogeneous or fine-grained materials, and incomplete saturation of samples (Robson, 1993).



Modified from Eckis, 1934

Figure 3: Relationship among porosity, specific yield and specific retention

3.1.3.2 Based on Moisture-Retention Data

The specific yield can be calculated from the moisture-retention data also by calculating the change in the unit area volume of air associated with a decline of the water table. The volume of air in the unsaturated zone per unit area is given by

$$V_a = \int_0^{z_1} (\phi - \theta) dh \quad \dots \quad (11)$$

where V_a is the volume of air per unit area, ϕ is the porosity, θ is the volumetric water content, h is the height above the water table (i.e., suction) and z_1 is the distance from water table to the top of aquifer. This equation assumes that the equilibrium condition prevails so that the capillary suction at a point above the water table is numerically equal to the height of the point above the water table. The above equation with z_1 replaced by z_2 applies for the calculation of air volume at a new water table z_2 . The difference between the two air volumes is equal to the volume drained or released per unit area. The specific yield can, therefore, be expressed as

$$S_y = \frac{\int_0^{z_2} (\phi - \theta) dh - \int_0^{z_1} (\phi - \theta) dh}{(z_2 - z_1)} \quad \dots \quad (12)$$

For non-homogeneous aquifer, the retention function $\theta(h)$ will be different for each layer. In the ideal case of a homogeneous aquifer, the distances z_1 and z_2 are equal to/or greater than the suction and thus the above equation becomes

$$S_y = \phi - \theta_r \quad \dots \quad (13)$$

3.1.3.3 Groundwater Estimation Committee (GEC), 1997 Norms

Specific yield can also be estimated using the Groundwater Estimation Committee (GEC), 1997 norms, which is basically derived from the ground water-budget method. According to this methodology, groundwater balance in non-monsoon season can be used to estimate the specific yield using the equation:

For command areas,
$$S_y = \frac{1}{A \cdot \Delta z} (Q_d - I_{rf} + Q_{bf}) \quad \dots \quad (14)$$

For non-command areas,

$$S_y = \frac{1}{A.\Delta Z} (Q_d + Q_{bf}) \quad \dots \quad (15)$$

where ΔZ is the difference in the pre-monsoon water level of the consecutive years, A = is the area of aquifer, Q_d is the groundwater draft, I_{rf} is the Irrigation return flow and Q_{bf} is the base-flow in non-monsoon season.

For non-command areas, assuming the base flow (Q_{bf}) to be small as compared to the other components in the non-monsoon season, specific yield (S_y) can be calculated as

$$S_y = \frac{Q_d}{A.\Delta Z} \quad \dots \quad (16)$$

3.1.4 Based on Borehole Geophysical Logs

The specific yield can also be estimated from specific retention by use of porosity data from geophysical logs. Evaluation of various porosity logs indicates that the density porosity log is well suited to measure the porosity in aquifer materials. Effects of errors in density porosity logs can be minimized by calculation of mean porosity for borehole intervals rather than relying on porosity values at specific depths (Robson, 1993). The porosity of a formation can be determined by use of geophysical logs, such as sonic logs, neutron logs, or density logs. Each of these logs can accurately estimate the porosity of a formation if equipment and conditions in the borehole closely approximate the assumptions used in developing the logs. *Sonic logs* are based on a number of assumptions that cannot be evaluated readily in the borehole without analyses of core samples. This limitation makes the sonic log the poorest indicator of porosity among the three logs (Keys, 1990). *Neutron logs* and density logs can produce comparable results. However, neutron logs are best suited to measure the porosity of dense materials of small porosity, and *density logs* are best suited to measure the porosity of low density materials of large porosity.

A density porosity log is calculated from the bulk density log by use of the equation:

$$\phi = \frac{P_g - P_b}{P_g - P_f} \quad \dots \quad (17)$$

where, ϕ = the porosity, P_g = the grain density, P_b = the bulk density of formation, and P_f = the fluid density. The specific yield is then estimated using equation (10).

3.1.5 Based on Inverse Modelling Techniques

Specific yield can also be determined by inverse modeling techniques. For this purpose, MODFLOW, MIKE Basin, groundwater modeling using other models, etc may be used. While using such models, the values of various input parameters are assigned except the specific yield, for which a trial value is assigned and model results are compared with the observed values. This trial-and-error procedure is repeated for various sets of specific yield value until the error between the observed and modeled values is within the permissible limits. Once the model is calibrated and validated, the value of specific yield for the given area is confirmed. In determining the specific yield value using the inverse modeling technique, it is assumed that all other set of parameter values used in the model are fairly accurate.

3.2 Software Tool for Estimation of Specific Yield (*Spicy_EsT*)

The software is Windows based and is developed in Microsoft Excel 2007. This is designed such that its operation is easy-to-handle. The software is intended to provide an easy computational support for the users working in the water sector. The software is developed by incorporating most of the techniques and methods presented above in this report. The capabilities of the developed software have been given under the section 3.0. A user's guide is also prepared for easy support to the users and is given as *Annexure-I*. The software comprises of following modules in the form of worksheets:

- Specific yield (S_y) estimation by specific methods.
- S_y estimation based on moisture-retention data.
- S_y estimation based on grain-size distribution.
- S_y estimation based on D_{90} grain diameter.
- S_y estimation based on correlation between specific retention and D_{90} grain diameter.
- Selection of methods of S_y estimation based on formation type.
- Selection of methods of S_y estimation based on availability of data.
- Unconfined aquifer parameter estimation from drawdown test.
- Confined aquifer parameter estimation from drawdown test.
- Confined aquifer parameter estimation from recovery test.

Specific yield values in tabular or graphical form for a variety of formation type.

4.0 RESULTS AND DISCUSSION

Various techniques for the estimation of specific yield and storage coefficient have been described above. These techniques have been categorized as field measurement techniques, laboratory methods, estimation techniques, borehole geophysical logs and inverse modeling technique. These techniques vary with respect to their spatial scale of assessment, economics, type and formation of aquifer, data requirements, accuracy and time-constraints. Keeping in view all these aspects, all above techniques have been studied and their merits and demerits have been assessed and presented in Table 5 in a summarized view.

Table 5. Merits and demerits of various methods and techniques of specific yield determination

S.N.	Technique	Merits	Demerits	Remarks
1	Field measurement			
a	Pump tests/ Slug tests	More accurate for the test site (most commonly used technique).	Costlier & knowledge of aquifer conditions (confined, unconfined, leaky, non-leaky, etc.) is essential for selection of aquifer-test method.	Precise measurement of discharge is necessary. Uncertainty due to underlying assumptions & heterogeneity on the spatial scale.
b	Field saturation and drainage	Suitable for unsaturated zone.	Cannot be applied under the saturated zone.	
c	Pumping method	In-situ technique.	Difficult to measure the volume of sediments drained.	Errors may be due to capillary action.
d	Recharge method	In-situ technique.	Difficult to measure the volume of sediments saturated.	Errors may be due to capillary action.

2	Laboratory Analysis			
a	Sample saturation and drainage	-	Less accurate and overestimates the specific yield. Site specific.	Large number of samples are needed to cover the basin.
b	Correlation with particle size	Speedy Method.	Approximate method. Site specific.	
3	Estimation techniques			
a	Based on grain size	Easier to apply.	Not accurate because of large variance in data relating grain size to specific yield and specific retention.	Compressibility effect is ignored.
b	Based on moisture-retention data	Suitable for homogeneous aquifers.	For non-homogeneous aquifers, moisture retention function is required for each layer and hence time-consuming.	
c	GEC, 97	Unit scale (block/taluka/mandal).	Approximate method. A number of assumptions are taken relating to groundwater draft, irrigation return flow, etc.	
4	Borehole geophysical logs	Accurate.	Costlier as bore logs are required at finer intervals.	
5	Inverse modeling	Accurate. Regional	Large number of	Accuracy depends on the

	techniques	scale.	data requirement.	accuracy of the input parameters/ variables.
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As mentioned above, the techniques of specific yield measurement vary with each other with respect to various aspects mentioned above, their data requirements also vary. Hence the data requirements of each technique are also examined and are given in brief in Table 6. These data will be required further for inter-comparison of these techniques and methods under varying range of field conditions.

Table 6. Data requirements of various techniques of specific yield determination

S.N.	Technique	Data Requirements
1	Field measurement	
a	Pump tests/ Slug tests	Ground water levels, hydraulic conductivity, pumping rate vs. time, distance of observation well.
b	Field saturation and drainage	Soil moisture content, porosity.
c	Pumping method	Groundwater level, volume of water pumped.
d	Recharge method	Groundwater level, volume of water recharged.
2	Laboratory Analysis	
a	Sample saturation and drainage	Column study data, volume of water yielded.
b	Correlation with particle size	Specific retention, effective size, or mean diameter of particles.
3	Estimation techniques	
a	Based on grain size	Grain size data, nomograph of grain size with porosity and specific retention.

b	Based on moisture-retention data	Moisture retention data.
c	GEC, 97	Ground water levels, ground water draft, irrigation return flow and base flow.
4	Borehole geophysical logs	Grain density, bulk density of formation, moisture retention data for various logs and fluid density.
5	Inverse modeling techniques	Ground water levels, rainfall/recharge, hydraulic conductivity, evaporation/ET, ground water draft, aquifer geometry, aquifer parameters, etc.

4.1 Suitability and priority of selection of various methods under varying field conditions

Variety of methods is available for the estimation of specific yield of aquifer formations. Each method has its own merits and demerits. However, the choice of method depends on the availability of funds, time-constraints, aquifer conditions, spatial scale and data availability. Moreover, in general, the aquifer material is normally heterogeneous and moreover the groundwater is dynamic in nature and its assessment, variation, draft and movement is on spatial scale, hence as a first priority, space-dependent methods for the estimation of specific yield (i.e. GEC-97 basically water-budget method, and inverse modeling technique) could be more practical and accurate provided the inputs used by these techniques are fairly accurate. The second priority methods could be the pump-tests/slug-tests and bore hole logs, which are on point scale but widely used in the field itself in the absence of laboratory analysis. But before applying these methods, the basin or the geographical unit shall be divided into various zones depending on the geo-hydrological conditions of aquifers, and specific yield/ storage coefficient shall be determined for each zone. The third priority methods could be based on laboratory analysis (i.e. sample saturation and drainage, and correlation with particle size) and estimation techniques (i.e. methods based on grain size and based on moisture retention data) which can only be handled with the support of laboratory. A qualitative assessment of these techniques and methods is presented in Table 7. However, the quantitative assessment of these techniques is yet to follow to find out the best possible methods and options for the determination of specific yield and storage coefficient under the varying range of real field conditions.

Table 7. Qualitative assessment on the suitability of various methods

1 st Choice	2 nd Choice	3 rd Choice
Water Budget (GEC-97) and Inverse modeling technique.	Pump-tests/slug-tests and bore hole logs.	Laboratory analysis based.
Space-dependent methods.	Site-specific methods and widely used in the field itself. Basin or the geographical unit shall be divided into various zones depending on the geo-hydrological conditions of aquifers, and specific yield shall be determined for each zone.	Sample saturation and drainage, correlation with particle size, methods based on grain size and based on moisture retention data.
More practical and accurate provided the inputs used by these techniques are fairly accurate.	Do not require Laboratory analysis.	Require Laboratory analysis.

4.2 Computation of Specific Yield and Storage Coefficient using the Developed Software

The specific yield can be estimated using numerous methods with the help of *SpicY_Est* software developed under the present study. A snapshot of the main screen of this software is given in Figure 4. The capabilities and modules of the software are described under section 3.0. Some of the screenshots for various uses are shown in Figures 5 and 6 for the estimation of specific yield and storage coefficient under varying range of field conditions.

Estimation of Specific Yield

Go To Method Selection

Select Methods	Assign Inputs				Specific Yield (%)	
<input type="checkbox"/> Skaggs (1978)	Area of Aquifer Formation (m ²)	Change in WT Position (m)	Initial Saturated Volumetric Soil Moisture (m ³ /m ³)	Volumetric Soil Moisture after lowering WT (m ³ /m ³)	4.00	
	100	5	45	41		
<input type="checkbox"/> Field Saturation & Drainage	Moisture Contents under Saturated Condition (%)		Moisture Contents after Drainage (%)		5.00	
	40		35			
<input type="checkbox"/> Pumping Method	Area of Aquifer Formation (m ²)	Decline in WT Position (m)	Measured Volume of Water Pumped (m ³)		0.27	
	456	400	500			
<input type="checkbox"/> Recharge Method	Area of Aquifer Formation (m ²)	Rise in WT Position (m)	Measured Volume of Water Recharged (m ³)		5.00	
	5000	2	500			
<input type="checkbox"/> Based on Laboratory Analysis	Porosity (%)		Specific Retention (%)		18.00	
	28		10			
<input type="checkbox"/> Sample Saturation & Drainage	Internal Diameter of Soil Columns (m)	Saturated Height of Soil Columns (m)	Height of Soil Columns Drained (m)	Volume of Water Yielded (m ³)	15.92	
	0.2	2	2	0.01		
<input type="checkbox"/> Correlation with Particle Size	Porosity (%)	D ₉₀		Specific Retention using Correlation between S.R. & Particle Size (D ₉₀)	33.00	
	41	1.976		8.00		
<input type="checkbox"/> Based on Grain Size	Grain Size Distribution		D ₉₀	Porosity (%)	33.96	
			1.976	41.55		
				7.58		
<input type="checkbox"/> Based on Moisture-Retention Data	Moisture-Retention Data		Porosity from Moisture Retention Data (%)		23.98	
			45.99			
			21.41			
<input type="checkbox"/> Based on WTF Method (GEC-97 Norms)	Area of Aquifer Formation, A (m ²)	GW Draft, Q _d (m ³)	Irrigation Return Flow, I _r (m ³)	Baseflow in Non-Monsoon Season, Q _b (m ³)	GW Table Decline during Non-Monsoon Season, Δh (m)	3.96
	5000	1000	30	20	5	
<input type="checkbox"/> Based on Borehole Geophysical Logs	Grain Density (g/cm ³)	Bulk Density of Formation (g/cm ³)	Fluid Density (g/cm ³)	Density Porosity (%)	Specific Retention from Moisture Retention Data (%)	12.27
	2.65	2.20	1.00	27.27	15	
<input type="checkbox"/> Lysimeter Experiment	C/s Area of Lysimeter Core (m ²)	Decline in WT Position (m)	Measured Volume of Water Drained (m ³)		5.00	
	50	2	5			
<input type="checkbox"/> Based on Inverse Modeling	Groundwater Modeling would be needed.					
<input type="checkbox"/> Pump-Test Methods	Unconfined Aquifer		Confined Aquifer		Formation like Specific Yield Values	
	Drawdown Test	Drawdown Test	Recovery Test			

Figure 4. Main window of the *SpicY_Est* software tool for the estimation of specific yield

Selection of Suitable Method(s) for Specific Yield Estimation

Selection Based on Formation Type/Data Availability →	Formation Type	Compute Specific Yield
Select: Formation Type →	Alluvium	Possible Methods
Select: Local Conditions →	Nil	Skaggs (1978) Field Saturation & Drainage Pumping Method Recharge Method Based on Laboratory Analysis Sample Saturation & Drainage Correlation with Particle Size Based on Grain Size Based on Moisture-Retention Data Based on WTF Method (GEC-97 Norms) Based on Borehole Geophysical Logs Lysimeter Experiment Based on Inverse Modeling Pump-Test Methods

Total Porosity = ● + ● = 30%
 Effective Porosity = ● = 15%

unsaturated
saturated thickness

total porosity

30% total porosity total moisture content

15% effective porosity available water supply (specific yield)

Figure 5. Screenshot showing the module for selection of method(s) based on formation type

Selection of Suitable Method(s) for Specific Yield Estimation		
Selection Based on Formation Type/Data Availability →	Formation Type Data Availability	Compute Specific Yield
Data for Specific Yield Estimation	Check Box for Data Availability	Possible Methods
Study Area/ Aquifer Area	<input checked="" type="checkbox"/>	Recharge Method Sample Saturation & Drainage Correlation with Particle Size Based on Grain Size
GW Levels	<input checked="" type="checkbox"/>	
Moisture in Soil Profile	<input type="checkbox"/>	
Pumping Rate	<input type="checkbox"/>	
Recharge Rate	<input checked="" type="checkbox"/>	
Porosity	<input type="checkbox"/>	
Specific Retention	<input type="checkbox"/>	
Column Experiment Details (Column Diameter, Saturated Height, Drained Height, Water Drained)	<input checked="" type="checkbox"/>	
Grain Size Distribution (Grain Size & Cumulative Weight % Passed)	<input checked="" type="checkbox"/>	
Moisture Retention Data (Suction Pressure vs. Moisture Contents)	<input type="checkbox"/>	
GW Draft	<input type="checkbox"/>	
Irrigation Return Flow	<input type="checkbox"/>	
Base Flow	<input type="checkbox"/>	
Grain Density	<input checked="" type="checkbox"/>	
Bulk Density	<input type="checkbox"/>	
Lysimeter Details (Area, WT Change & Measured Volume of Water)	<input type="checkbox"/>	
Pump Test Data (Pumping Rate, Time vs. Drawdown, Well Details, Aquifer Depth & Details)	<input type="checkbox"/>	
Aquifer Geometry, Surface Topography, Lithologs, Stream & Canal Details and Flow Data, GW Recharge, ET, Hydraulic Conductivity)	<input type="checkbox"/>	

Figure 6. Screenshot showing the module for selection of method(s) based on available data

5.0 SUMMARY AND CONCLUSIONS

The present work was envisaged the estimation of specific yield and storage coefficient under varying range of field conditions. A compilation on the estimation of specific yield and storage coefficient is done by carrying out comprehensive review of literature. The work comprises of various methods and techniques for the estimation of specific yield and storage coefficient including their merits and demerits, and also the data requirement of each method. Most of these methods give the specific yield on the point scale except the GEC-97 methodology and inverse modeling technique which give the specific yield at the basin or geographic unit scale. A discussion is also made on the prioritization on the use of various methods of specific yield estimation. The developed software tool (*SpicY_Est*) is very handy and easy-to-use for the estimation of specific yield and storage coefficient as well as deciding the suitable method based on data availability and formation types. This report and the developed software tool would be helpful to researchers, groundwater professionals and field engineers as an option for selection of appropriate method and computation of specific yield and storage coefficient for management of groundwater resources.

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