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Geostatistics and Geospatial Technologies for Groundwater Resources in India

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Dedicated to

The Millions of Farmers of India

Foreword

Groundwater is the primary source of freshwater in many parts of the world. Some regions are becoming overly dependent on it, consuming groundwater faster than it is naturally replenished and causing water tables to decline unremittingly. Despite the increasing stress placed on water resources by population growth and economic development, the laws governing groundwater rights have not changed accordingly, even in developed nations. Not only the groundwater depletion is limited to dry climates, but also the pollution and mismanagement of surface water can cause over-reliance on groundwater in regions where annual rainfall is abundant.

In this context, I am delighted to learn that Springer Nature is publishing a book on *Geostatistics and Geospatial Technologies for Groundwater Resources in India*, in the Springer Hydrogeology series. The book is jointly edited by Partha Pratim Adhikary, Pravat Kumar Shit, Priyabrata Santra, Gouri Sankar Bhunia, Ashwani Kumar Tiwari, and B. S. Chaudhary who are eminent scholars and researchers in the field of groundwater and geospatial technology.

India, arguably one of the most densely populated parts of this planet, hosts about 19% of the world's population, within only $\sim$2.5% of the total global land area. Although, the region encompasses three of the most extensive riverine systems of the world (Indus, Ganges and Brahmaputra river basins) that host several of the high groundwater-producing aquifers of the globe, the availability of safe and sustainable groundwater in the region is not consistent, and there is a growing concern about the accessibility of safe water in many of these aquifers (e.g., Ganges basin) due to presence of geogenic pollutants. Moreover, the groundwater from these trans-boundary aquifers has become a politically sensitive issue. The region is also the most extensive user of groundwater resources on the globe, leading to severe concern of groundwater availability, even for groundwater affluent aquifers. Several anthropogenic activities, particularly irrigation (accounts for >80% of the groundwater withdrawal), lead to groundwater depletion in most of areas within the region. Varying precipitation rates and sub-surface hydraulic condition are providing more challenges to groundwater governance. Further, ongoing and proposed urbanization rate in India has skewed the distribution of population and their water footprint. Unregulated growth of urban areas, particularly over the last two decades, without infrastructural services for proper collection, transportation, treatment, and disposal of domestic wastewater led to increased pollution and health hazards.

This forthcoming book has been very effectively organized into four thematic sections: Section-I covers the fundamentals of geostatistics and geospatial technologies, Section-II represents groundwater availability: exploration, depletion, recharge and storage, Section-III evaluates the groundwater quality and pollution assessment and Section-IV illustrates application of GIS, and geostatistical techniques in groundwater resource management.

It is a cohesive effort of a number of authors, researchers, and experts in the groundwater across the country and other parts of the world. The editors have done an exemplary job in collecting the papers, compiling, and editing them in a book form. The quality of this interdisciplinary research can be realized by readers by going through chapters in this enriched volume. This book will be very beneficial for hydrologists, geographers, soil scientists, students, scientists, agriculturalists, and policymakers.

I extend my warmest greetings to editors, authors, and all those associated with the publications of this book and wish them a wide readership.

Yours truly,

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Preface

India is the largest user of groundwater in the world using an estimated 250 km^3 of groundwater per year. Groundwater contributes 62% in agriculture sector, 85% in rural water supply, and 45% in urban water consumption in India. Therefore, groundwater is inarguably India's single most important natural resource and the foundation of the livelihood security of millions of Indian farmers. However, this precious water resource is under increasing pressure due to the intensification of human activities along with climate change. In India, about 36% of groundwater blocks are semi-critical, critical, or overexploited and the situation is deteriorating rapidly. Not only groundwater depletion is unprecedented, its quality is also deteriorating on an alarming rate throughout India. Therefore, water supply situation from groundwater is expected to become more severe in the future.

Even as groundwater has helped the country to become self-sufficient in food production, the country is now facing a crisis of depleting water tables and water quality. The deep drilling by tube wells that was once part of the solution to the problem of water shortage now threatens to become a part of the problem itself. The country, therefore, needs to pay urgent attention to the sustainable and equitable management of groundwater. The prospects of continued high rates of growth of the Indian economy will depend critically on how judiciously we are able to manage groundwater in the years to come.

Geospatial techniques and tools like geostatistics, remote sensing, and geographic information system play an important role in depicting the spatio-temporal variation of water level and water quality. The advances and applications of RS, GIS, and geostatistical techniques to solve the twin problems of groundwater quantity depletion and quality deterioration are a researchable topic and need further discussion.

The present book entitled *Geostatistics and Geospatial Technologies for Groundwater Resources in India* has covered elucidation-based groundwater problem-solving strategies with the help of geospatial techniques in a precise and clear manner to the research community to achieve in depth knowledge in the field. It will help those researchers who have an interest in this field to keep insight into different concepts and their importance for applications in real life. This book advances the scientific understanding, development, and application of geospatial technologies related to water resource management. Further, it will be helpful in the planning of future research strategies in the field of groundwater management.

We thank all the authors who have meticulously completed their chapters at short notice and contributed in building this edifying and beneficial publication. We believe, this book will be of great value to geographers, geologists, geophysicists, agriculture engineers, hydrologists, soil scientists, ecologists, research scholars, environmentalists, and policymakers.

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Medinipur, India — Pravat Kumar Shit
Jodhpur, India — Priyabrata Santra
New Delhi, India — Gouri Sankar Bhunia
New Delhi, India — Ashwani Kumar Tiwari
Kurukshetra, India — B. S. Chaudhary

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The preparation of this book has been guided by several hydrologic pioneers. We are obliged to these experts for providing their time to evaluate the chapters published in this book. We thank the anonymous reviewers for their constructive comments that led to substantial improvement to the quality of this book. Because this book was for a long time in the making, we want to thank our family and friends for their continued support. Dr. Partha Pratim Adhikary thanks ICAR-Indian Institute of Soil and Water Conservation, Research Center, Koraput, Odisha, for its support to edit this book. Dr. Pravat Kumar Shit thanks Dr. Jayasree Laha, Principal, Raja N. L. Khan Women's College (Autonomous), Midnapore, for her administrative support to carry out this project. This work would not have been possible without constant inspiration from our students, knowledge from our teachers, enthusiasm from our colleagues and collaborators, and support from our family. Finally, we also thank the publisher and its publishing editor Dr. Alexis Vizcaino, associate publishing editor Dr. Ali Khan, and production administrator Karthik Raj Selvaraj, Springer Nature, for their continuous support in the publication of this book.

Executive Summary

The book contains four sections. In the first section, we discussed the fundamentals of geostatistics and GIS techniques, which have potential applications for groundwater assessment. Overall, these fundamentals are tried to capture in five chapters of the section. These chapters are essential either to understand the spatial process of groundwater variation or to quantify these variations further. Spatial assessment of groundwater can be done easily if understanding the spatial processes governing the spatial variation of this natural resource is clear. Chapter "Fundamentals of Geostatistics for Assessing Spatial Variation of Groundwater Resources" of the section covers basic fundamentals of geostatistics, e.g., concept of regionalized variable, random distribution, spatial interpolation, semivariogram, autocorrelation, etc. Further, the kriging processes along with its different variants are discussed. The kriging is defined as a spatial interpolation technique in which spatial variation structure of the target variable is utilized and it is quite different from classical interpolation techniques, e.g., inverse distance weighting, spline, etc. In Chapter "Recent Trends in GIS and Geostatistical Approaches to Analyze Groundwater Resource in India," application of geographic information system (GIS) and geostatistics for analyzing the status and changes of groundwater resources is highlighted, which will help the policymakers and managers to implement proper regulations for the sustainability of this precious resource in India. Moreover, the status of availability of groundwater in India along with its present situation in different applications is discussed in the chapter. Recently, artificial intelligence (AI) has been gaining much attention as a computational tool with an impressive performance over conventional techniques. Therefore, Chapter "Concept of Artificial Intelligence and Its Applications in Groundwater Spatial Studies" of the section devotes on the discussion on artificial intelligence and different soft computation methods and machine learning techniques and its applications in groundwater management. For example, artificial neural networks (ANNs), fuzzy logic (FL), wavelet transformation (WT), etc. are discussed in detail in this chapter. Moreover, the combination of one or more of methodologies has resulted in the emergence of new categories like a neuro-fuzzy (NF) technique, which is more powerful than individual methods. We further emphasize on learning the design, implementation, and application of individual and hybrid AI techniques on groundwater studies. In Chapter "Multi-criteria Decision-Making Approach Using Remote Sensing and GIS for Assessment of Groundwater Resources" of the section, multi-criteria decision-making approach in GIS environment for assessment of groundwater potential is discussed. As groundwater recharge and its availability depend on some geophysical factors, multi-criteria decision-making approach can be suitably applied to identify the groundwater potential zones. An example of its application for assessment of groundwater potential in Purulia District of West Bengal, India, is discussed too in the chapter. Chapter "Hydrogeochemical Characterization of Groundwater Using Conventional Graphical, Geospatial and Multivariate Statistical Techniques" of the section deals with graphical, geospatial, and multivariate statistical techniques for characterization of groundwater. In this chapter, cluster analysis, bivariate plots, factor analysis, Wilcox classifications, etc. are discussed which are used as an example study to characterize bore wells. Overall, the section provides suitable information on geostatistics and GIS along with various geospatial analyses for groundwater assessment and their management.

Section two of the book deals with the groundwater availability and its exploration, depletion, recharge, and storage for use in different purposes. As per the report of Central water Commission (2015), the water resource potential of India in terms of natural runoff in the rivers is about 1869 Billion Cubic Meter (BCM)/year. Out of which, the operational water resources have been assessed as 1123 BCM/year, in which 690 BCM/year is shared by surface and 433 BCM/year by groundwater. The net annual groundwater obtainability in India is 398 BCM. With the increase of population in India, the national per capita annual availability of water has reduced from 1816 cubic meters in 2001 to 1544 cubic meters in 2011 which is reduced approximately by 15%. Management of groundwater in future will entail a configuration of forward-thinking governance, innovative public grant, and educated participants. Approximately, 65% of India's overall aquifer is characterized by hard rock aquifers of peninsular India which is a low-storage aquifer system and the water level tends to drop very rapidly by more than 2–6 m over a decade. Alluvial aquifers of the Indo-Gangetic plain have substantial storage spaces and freshwater supply potential. However, due to extreme groundwater withdrawal and low recharge rates, aquifers are at menace of irreparable overexploitation. Aquifers provide a natural infrastructure for collecting, filtering water, and providing long-term and short-term storage without evaporative loses. Aquifers are the inexpensive natural set-up that could be used to deliver a stable water source for generations. However, without proper management, this natural infrastructure can deteriorate and become unstable, requiring substantial financial investments to collect, store, and treat water for use. Recently, groundwater science has grown up vastly through the expansion of novel monitoring tools and amended computational technologies that empower sophisticated modeling. The data sources of groundwater varying from new satellites to low-cost well monitoring have instigated to develop new intuition. Present section of the groundwater book summarizes exploration, depletion, recharge, and storage of groundwater and offers various geospatial approaches in terms of groundwater availability.

The application of geostatistics and other related modern tools for ensuring groundwater availability has been discussed in nine chapters. Chapter "Efficacy of Geospatial Technologies for Groundwater Prospect Zonation in Lower Western Ghats Area of Maharashtra, India" focused on efficacy of groundwater potential zone identification on lower Western Ghats (Central India) using geospatial technology and observed that MCDA approach is most appropriate than MIF. In Chapter "Identifying Suitable Sites for Rainwater Harvesting Structures Using Runoff Model (SCS-CN), Remote Sensing and GIS Techniques in Upper Kangsabati Watershed, West Bengal, India," the Upper Kangsabati Watershed has been considered for constructing rainwater harvesting structures using runoff model. Thirty-three check dams, twenty-eight minor irrigation tanks, and eleven percolation tanks locations were suggested for constructing sustainable rainwater harvesting structures. Chapter "Identification of Groundwater Potential Areas Using Geospatial Technologies: A Case Study of Kolkata, India" focused on the identification of potential zone for groundwater-based weighted overlay technique and summarized that most of the zone of Kolkata Municipal Corporation comes under the low potential zone for groundwater. Chapter "Geospatial Assessment of Groundwater Potential Zone in Chennai Region, Tamil Nadu, India" concentrates on Chennai region for assessing groundwater potential zone and found that western and south western zones are dominant for groundwater storage. Chapter "Identification of Groundwater Potential Zones Using Multi-Influencing Factors (MIF) Technique: A Geospatial Study on Purba Bardhaman District of India" identified the groundwater prospective zone in Purba Bardhaman District using statistical and geospatial techniques, and the outcome of the study suggested that 20.65%, 45.61%, and 33.74% of the total area comes under high potential, moderate potential, and low potential zone. Chapter "Delineating the Status of Groundwater in a Plateau Fringe Region Using Multi-Influencing Factor (MIF) and GIS: A Study of Bankura District, West Bengal, India" described the groundwater potential areas delineation in a plateau fringe region of the tropical environment and result indicates the poor to a fairly good condition of groundwater potentiality in all over the study area that is Bankura District of India. In Chapter "Aquifer Vulnerability Assessment of Chaka River Basin, Purulia, India Using GIS-based DRASTIC Model," DRASTIC model was used after integrating with GIS to identify vulnerable aquifer zones of Chaka river basin and suggested remedial measures for efficient planning and management. Chapter "Assessment of Water Level Behavior to Investigate the Hydrological Conditions of Bokaro District, Jharkhand, India Using GIS Technique" investigated the groundwater level conditions of Bokaro District and find out the relative impact of the different hydrometeorological and hydrogeological factors. Chapter "Investigation of Lineaments for identification of Deeper Aquifer Zones in Hard Rock Terrain: A Case Study of WRWB-2 Watershed from Nagpur District, Central India" has made an attempt to verify the influence of lineaments on groundwater regime in hard rock areas by employing the remote sensing technique and revealed that the yield of the borewells tapping deeper aquifers is highly influenced by the presence of lineaments. Overall, this section emphasized the application of geostatistics to explore and use the groundwater potential in India.

The third section of the book deals with the groundwater pollution and its assessment using geospatial techniques. The quality of groundwater is the appearance of combine influence of numerous physical, chemical, biological and radioactive elements. Polluted water may be hazardous to human health and cause diseases such as cancers, neurological disease, and cardiovascular disease. In India, only 12% of people can access good quality of drinking water and near about 85% of the rural population solely depends on specified groundwater sources, which is depleting at a faster rate. The high fluoride, salinity and arsenic content in groundwater are the major chemical-related problems of the whole of India. Subsequently, the issue of sustainability and maintenance of the standard quality of supplied drinking water and irrigation water is an area of concern for regions where groundwater is the main source.

Seven chapters are there in this section. Chapter "Assessing Contamination of Groundwater with Fluoride and Human Health Impact" elaborately discussed the groundwater contamination by fluoride and its consequently human health impact. Chapter "Primary Concept of Arsenic Toxicity: An Overview" focused on overview of arsenic toxicity and its impact on human organs. Fluoride and arsenic are the two of the most important groundwater contaminants affecting minions of people. Therefore these two chapters will be beneficial to tackle the health affect from these two pollutants. Chapter "Evaluation of Groundwater Quality by Use of Water Quality Index in the Vicinity of the Rajaji National Park Haridwar, Uttarakhand, India" discussed about the groundwater quality in Rajaji National Park and its surrounding regions, Haridwar, Uttarakhand, India using field-based measurement and also focused on the importance of monitoring for proper risk assessment of groundwater contamination. Chapter "Assessment of Groundwater Resource Pollution in Kangsabati River Basin, Paschim Medinipur, West Bengal, India" evaluates the degree of groundwater pollution in Kangsabati river basin, Paschim Medinipur District, West Bengal in India using field-based monitoring and measurement. It also suggested proper management practices to cope up with groundwater contamination in this river basin. Chapter "Effect of Conventional Sand Mining along Heavy Mineral Beach Placers and Its Environmental Impact" discusses the effect of saltwater intrusion in the coastal aquifer and the influence of sand mining on the quality of groundwater in the coastal region of Odisha state in India. The coal mining has a profound effect on groundwater pollution and colliery areas are in general polluted with heavy metals and other minerals are presented in Chapter "Evaluation of Shallow Groundwater Quality Index: A Case Study for a Coal Mining Environment (East Bokaro Coalfield) of Damodar valley, India." In the final chapter of the section, that is Chapter "Spatial and Temporal Categorization of Groundwater Quality for Domestic Use in Hisar District, Haryana, India" deals with the detailed study of groundwater pollution in watershed level and concluded with suitable recommendations to mitigate this problem. Overall, this section has provided the readers with an exhaustive overview of our current understanding of groundwater quality and pollution level through geospatial and geostatistical technology for better management of geographical regions. All chapters cover extensively the literature and present new results and ideas for future work.

The section four of this book specifically deals with the application of GIS and geostatistical techniques in groundwater resource management. Nine chapters have been devoted under this section. Chapters "Mapping Groundwater Level Fluctuation and Utilization in Puruliya District, West Bengal," "Mapping Groundwater Recharge Potential Zones Using GIS Approaches and Trend of Water Table Fluctuation in Birbhum District, West Bengal, India" and "Spatio-temporal Dynamics of Groundwater Resources of National Capital Region, Delhi" of this section deal with the seasonal and annual fluctuation of groundwater level and how to manage this resource under this varying fluctuation condition. The highly exploitative zones were identified and the zones where potential recharge can be possible were also mapped in these chapters. In this context, the efficacy of multi-influencing factor and analytical hierarchy process for groundwater management was established. Chapter "Groundwater Hydrology in Arid Rewari District of Haryana: Assessment, Development and Management Options" assessed the groundwater hydrology of the arid western region of India and discussed different development and management options. The understanding of hydrological dynamics will help toward the design of speedy groundwater management plans such as artificial recharge on large scale through rainwater harvesting, regulation on groundwater development in overexploited and critical areas, development of groundwater sanctuaries, power tariff on withdrawal of groundwater, conjunctive use of water, etc. These measures will certainly bridge the gap between groundwater availability and demand. The use of environmental isotopes to manage groundwater resources was dealt with in Chapter "Environmental Tracers and Isotopic Techniques: Tools for Sustainable Water Management." It will help to understand the use of isotopic techniques and environmental tracers in ecohydrology and groundwater studies. The applicability of the stable isotopes, noble gases as environmental tracers in water flow, and contaminant transport study has been discussed in detail. This chapter will be helpful in designing experiments and field scale observation stations for investigation of groundwater pollution loading and implementation of management plan. Chapter "Integrated Watershed Conservation and Management of Koshalya-Jhajhara Watershed, North India" discussed about the positive impact of integrated watershed management and conservation to augment the groundwater resources of India. The effect of proper implementation of watershed management plans has been visualized in the increase in groundwater resources of the watershed, which is a complex impact of change in land use, geomorphology, vegetation cover, socio-economic condition of the peoples living in the watershed, surface hydrology, etc. Water resources management for irrigated agriculture in perspective of geospatial techniques was discussed in Chapter "Water Resources Management for Irrigated Agriculture in Perspective of Geospatial Techniques." Chapter "Climate Change Impacts on Hydrology of a Small Watershed in a River Valley Project Catchment of Southern India" discussed the modeling technique like the use of SWAT model to manage the groundwater resources under climate change condition. The efficacy of hydrological model like SWAT to deal with the complex hydrological situation of a river basin under various climate change scenario has been discussed in this chapter. This chapter showed the effects of climate change on future agricultural production and alerted us about the required change that we have to undergo to cope up with the future harsh climatic conditions. The last chapter deals with the economic aspect and econometric management of groundwater with India centric considerations. Overall, this section clearly described the importance of geospatial techniques for suitable management of groundwater resources to get sustainable ecological and economical benefit.

Contents

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Fundamentals of Geostatistics for Assessing Spatial Variation of Groundwater Resources

Priyabrata Santra and Partha Pratim Adhikary

Abstract The natural resources on the earth seem to be randomly distributed but their variations over space and time are not all random. They exhibit a spatial correlation. This spatial correlation can be captured by geostatistics. Geostatistics deals with the analysis and modelling of geo-referenced data. The point observations are analyzed and interpolated to create spatial maps. For geostatistical interpolation, first the spatial correlation structures of the parameter of interest are quantified and then spatial interpolation is done using the quantified spatial correlation and optimal predictions at unobserved locations to create a map. In this chapter, the fundamental of randomness and statistical distribution are discussed. The statistical measure of spatial variation is the variogram which characterize the degree of spatial correlation. The quantification of variogram is also discussed in detail. Different interpolation techniques like kriging and its variations are also discussed. The fundamentals of ordinary kriging, indicator kriging and regression kriging are also described and their application aspects are also highlighted. The cross-validation procedure and the errors in geostatistical interpolation have also dealt in detail. The chapter ended with sampling design optimization and stochastic simulation processes, showing their importance and application in groundwater resources. This chapter will help the students, researchers and natural resources managers to understand the fundamentals of geostatistics and their application.

Keywords Cross validation · Kriging · Nugget · Semivariogram · Sill · Stochastic simulation · Range

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1 Introduction

Geostatistics is fundamentally different from classical statistics in the sense that it deals with the analysis and modelling of geo-referenced data. Its main aims are to quantify spatial variability and to create maps from point observations and thus can be easily applied on ground resource assessment. In this chapter, it is emphasized on how the spatial variability is assessed and further geostatistical interpolation is done.

In geostatistical interpolation, the first step is to quantify the spatial correlation structure of the variable of interest; for example, groundwater depth or groundwater quality parameters here (Adhikary et al. 2010). This can be done by examining the spatial observations on groundwater parameters and how these change in spatial domain. In the next step, spatial interpolation is done using the quantified spatial correlation and optimal predictions at unobserved locations to create a map. During the process of prediction, interpolation error is quantified as well, which helps to design optimal spatial sampling schemes that balance data collection costs and map accuracy (Santra et al. 2008). All this will be explained in this chapter, but in order to do so we first need to discuss the statistical theory that underlies geostatistical interpolation followed by representation of the spatial correlation structure, the basics of geostatistical interpolation ('kriging'), kriging extensions and spatial stochastic simulation.

2 The Random Field Model

Geostatistical methods are based on a statistical model of reality. This model treats reality in such a way that it is an outcome or a 'realization' of a stochastic spatial process. To describe the spatial process in detail, there is need to explain few basics of probability theory and statistics. For example, one need to understand about random variable, normal distribution, correlation, covariance etc.

2.1 Random Variables

Random variables are variables whose values depend on the outcome of a probabilistic experiment. A typical example is the throw of a (fair) die. If we denote this outcome by D, then D is a random variable that has six possible outcomes: 1, 2, 3, 4, 5 and 6. Each outcome has equal probability (namely 1/6), which means that D has a uniform probability distribution, as depicted in left side graph of Fig. 1. Now suppose that we perform the experiment and throw the die. Let the outcome be 5. Then $d = 5$ is the realization of D. Note that we introduced notation in which random variables are written in upper case and realizations in lower case. Realizations are just numbers; they are not stochastic but deterministic.

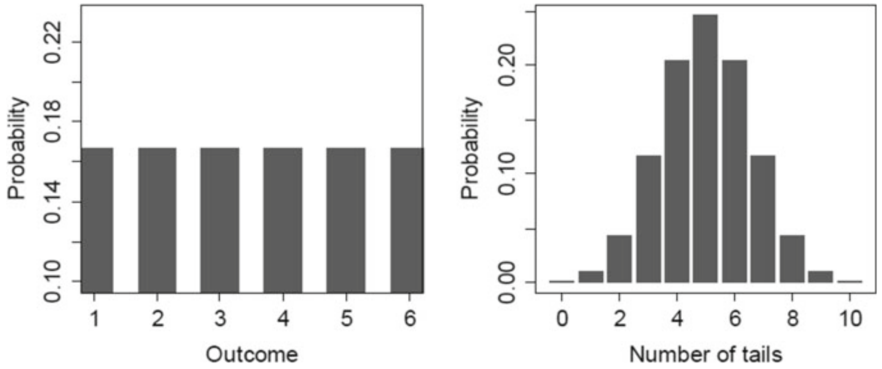

Fig. 1 Probability distribution of the throw with a die (left) and of the number of tails of ten tosses with a coin (right) (Adapted from Santra and Heuvelink, 2018)

Another example of a random variable is the number of tails ('successes') of ten tosses with a coin. The possible outcomes are all whole numbers between zero and ten. The probability distribution is no longer a uniform distribution because the probabilities are not equal for all outcomes, as depicted in right side graph of Fig. 1. For instance, the probability of zero successes is much smaller than that of three successes, and this in turn is smaller than that of five successes. If we denote this random variable by K, then we have probability $P(K = k) = \binom{10}{k}\left(\frac{1}{2}\right)^{10}$ for all k between zero and ten. The probability distribution of K is an example of the binomial distribution.

Key properties of a random variable are its mean and variance. The mean is also known as the expected value. It is calculated by taking a weighed sum of all possible outcomes of the random variable, using the probability of each outcome as a weight. Thus, we can calculate the mean of a throw with a die as:

$$\mathrm{E}[D] = \sum_{d=1}^{6} d \cdot P(D = d) = \sum_{d=1}^{6} d \cdot \frac{1}{6} = \frac{1}{6}\sum_{d=1}^{6} d = \frac{1}{6}(1 + 2 + 3 + \cdots + 6) = 3.5 \tag{1}$$

Here, $\mathrm{E}[D]$ stands for expected value. It is custom to denote the mean of a random variable by the Greek letter μ. The mean may be interpreted as the average outcome of a very large (infinite) number of repetitions of the same probability experiment. In other words, if we would throw the die 1 million times, then the average of these 1 million throws would be very close to 3.5.

The variance is the expected value of the square of the difference between the random variable and its mean. It is typically denoted by σ^2. For the throw with a die we get:

$$\sigma^2 = Var(D) = E[(D - E[D])^2] = \sum_{d=1}^{6}(d - 3.5)^2 \cdot P(D = d)$$
$$= \frac{1}{6}\sum_{d=1}^{6}(d - 3.5)^2 = 2.92 \tag{2}$$

The standard deviation is the square-root of the variance (i.e., σ). It is a measure of the spread or variability of the random variable, while the mean is a measure of centrality or central tendency. Other measures of centrality are the median and mode. The median is the value that separates the probability distribution of a random variable in two halves of equal probability mass (e.g., if X is a random variable then $(X < median) = (X > median) = 0.5$). The mode is that outcome of a random variable that has the largest probability.

The two examples discussed so far are examples of a discrete random variable. These are random variables that have a finite number of outcomes (or countably infinite). The opposite are continuous random variables, which have an (uncountable) infinite number of outcomes. For instance, let U be a randomly chosen real number between 0 and 1. Because there are an infinite number of outcomes, each outcome has equal probability and because all probabilities must sum to one, we have $P(U = u) = 0$ for any value of u. This implies that we cannot characterize a continuous random variable by the probabilities associated with each possible outcome. Instead, we must use the concept of probability density. We can calculate the probability that U takes on a value within a given interval $[a, b]$ by mathematical integration:

$$P(a \leq U \leq b) = \int_a^b f(u)\mathrm{d}u \tag{3}$$

Here, f represents probability density. If you are not familiar with mathematical integration, then it may help to know that the integration sign is nothing else than a twisted letter 'S', which signifies that we sum from a to b, in very much the same way as we used the $\sum$ symbol to represent summation over the outcomes of a discrete random variable. For random variable U, which has a uniform continuous distribution between 0 and 1, we have $f(u) = 1$ for all u in the interval [0,1] and so $P(a \leq U \leq b) = \frac{1}{b-a}$ (assuming $0 \leq a < b \leq 1$).

3 The Normal Distribution

The most common continuous probability distribution is the normal distribution. Let X be a normally distributed random variable, then its probability density is given by:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}}\mathrm{e}^{\frac{(x-\mu)^2}{\sigma^2}} \tag{4}$$

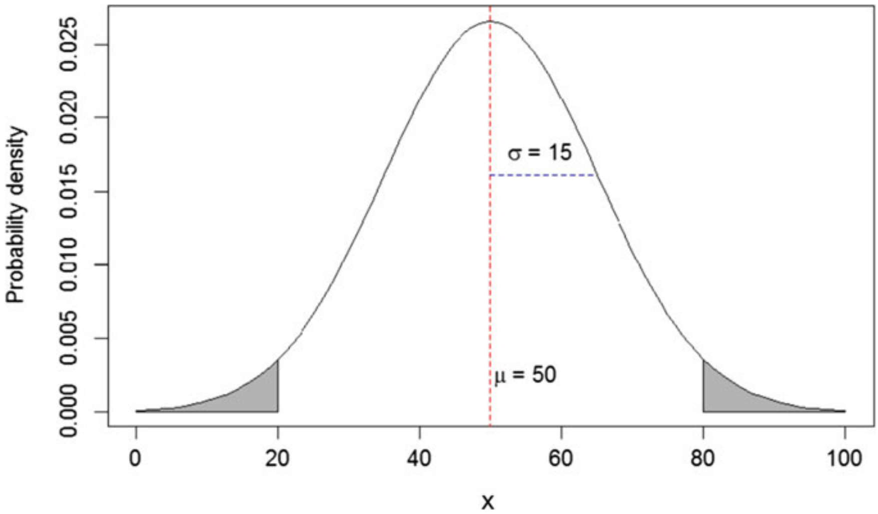

Fig. 2 Probability density of a random variable X that has a normal distribution with mean $\mu = 50$ and standard deviation $\sigma = 15$. The probability of values that deviate more than two standard deviations from the mean (grey area) is about 0.05 (Adapted from Santra and Heuvelink, 2018)

where μ and σ^2 are parameters. If we calculate the mean and variance of X in a similar way as was done for D above (but then using integration instead of summation), we get that the mean of X equals μ while its variance equals σ^2 (this also explains why we used these symbols). The shape of the normal probability density is the well-known bell-shaped curve and an example is given in Fig. 2. Beware not to interpret the numbers on the y-axis as probabilities. In case of continuous random variables, probabilities can only be associated with the surface area below the curve. The total area below the curve must always be equal to one.

The importance of the normal distribution can be realized from the *Central Limit Theorem* of statistics. It states that the distribution of averages of realizations that are randomly and independently drawn from whatever distribution will tend to be the normal distribution. For instance, the height of a person is the cumulative effect of many factors, such as genetic material, food supply and illnesses during childhood, and so whenever we plot the frequency distribution of a person's height from a sufficiently large sample of adults drawn from a population, this distribution will be remarkably normal. This is illustrated also in Fig. 3, which shows that the number of tails with repeated tossing of a coin converges to the normal distribution as the number of tosses increases. Indeed, many variables encountered in the environmental sciences, such as air temperature, clay content of the soil or river water flux, fit the normal distribution curve fairly well. There are also many variables that follow better a *lognormal* distribution, such as the concentration of pollutants in the ground- or surface water. Such variables typically result from *multiplication* instead

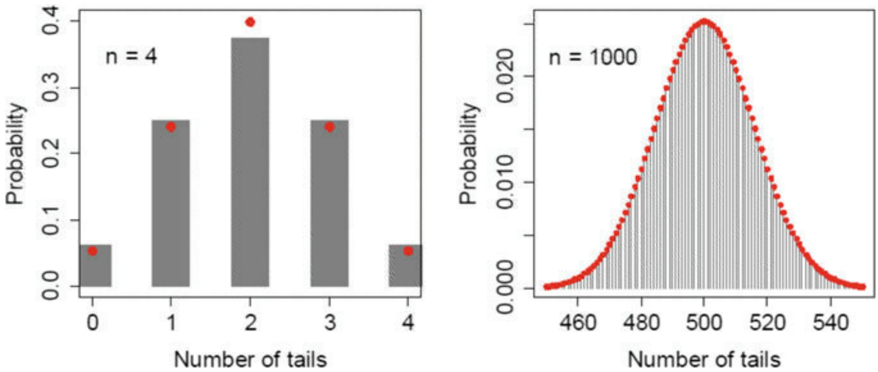

Fig. 3 The probability distribution of the number of tails when tossing a coin progressively approaches the normal distribution with increasing number of tosses (*n*). Grey bars represent the factual binomial distribution; red dots represent the normal distribution (Adapted from Santra and Heuvelink, 2018)

of *summation* of underlying random variables. The lognormal distribution is asymmetric and has a non-zero *skewness*. A random variable is lognormally distributed if its log-transform is normally distributed.

In geostatistics, we mainly work with normally distributed random variables. Not only because the normal distribution is often encountered in the real world, but also because the *statistical inference* associated with normally distributed random variables is much easier than with others. Whenever we come across a variable that deviates substantially from normality, we will look for a *mathematical transformation* (e.g., logarithm, square-root) such that the transformed variable is (approximately) normal.

4 Probability Distribution Versus Frequency Distribution

Above we explained that random variables are characterized by a probability distribution, such as the uniform and normal distribution. The attentive reader might ask, how can the observed data of an environmental variable have a probability distribution? It is not a random variable, it is a data set (i.e., a characteristic measured on a *population* of objects or on a *sample* from such population). Indeed, there is a subtle but important difference between the two. Whereas a random variable has a *probability distribution*, a data set has a *frequency distribution*. A frequency distribution shows how often a certain value (or range of values) occurs within the dataset, while a probability distribution shows the probability of a certain outcome of a probability experiment. Now if we define a random variable as the outcome of a *random draw* from the dataset, then it turns out that the probability distribution of that random variable equals the frequency distribution of the data.