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Modelling fluid flow through fractured reservoirs: is it different from conventional classical porous medium?

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Two-thirds of peninsular India being composed of hard rocks, a thorough understanding of fluid flow through fractured aquifers becomes inevitable in order to address groundwater recharge and contaminant transport problems, and subsequently to deduce better groundwater management decisions. In this context, an attempt has been made to clearly delineate fundamental differences associated with conceptual modelling of fluid flow through a fractured reservoir from that of conventional classical porous medium. The differences deduced from this study convey that fluid flow through a fractured reservoir deserves special attention and its associated fluid flow analysis cannot be simplified using conventional Darcy-based approach. Further, a brief discussion on the upscaling issues associated with the fractured reservoir is given and the study demonstrates that the upscaling issues associated with a classical porous medium cannot be directly applied to analyse fluid flow through a fractured reservoir.

Keywords: Darcy, fluid flow, fractured reservoir, porous medium, upscaling.

IT is well-known that two-thirds of peninsular India is composed of hard rocks with the inclusion of Deccan Traps as well. This hard rock terrain is essentially drought-prone and heavily depends on the use of groundwater. Groundwater aquifers in such hard rock terrain are predominantly unconfined in nature, and subsequently the respective watershed and its associated groundwater system are directly connected. However, the groundwater flow associated with such unconfined aquifers generally do not follow the surface gradient as observed in a typical homogeneous porous medium. As a result, the discharge from such aquifers does not necessarily get into streams and/or rivers, and subsequently, the estimation of base flow component remains extremely challenging. In other words, the knowledge of fluid desaturation and its associated water level fluctuation within a hard rock aquifer system remains a mystery as it fundamentally requires a knowledge of fluid migration within a hard rock aquifer system. Since the hard rock geological unit is generally associated with a particular degree of fracturing resulting

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from various parameters ranging between imbalances in tectonic forces at larger continental scale and physical/chemical weathering at local scale, the term hard rock aquifer hereafter will be referred to as a fractured aquifer; and the study is limited to saturated subsurface fluid flow. In reality, however, predominantly, the same approach as applied for a classical porous medium is used to study the groundwater flow analysis for a fractured aquifer. In some cases, the concept of equivalent porous medium (EPM) is applied by considering the effective values of fundamental aquifer parameters. In this context, the purpose of this study is to delineate the conceptual modelling differences between a classical porous medium and a fractured reservoir at a fundamental level, and subsequently to provide better insights to groundwater stakeholders involved in taking critical groundwater management decisions associated with a fractured reservoir.

A porous/permeable groundwater aquifer is a complex geological unit where groundwater exists in the pore spaces of a typical porous medium with significant formation or media permeability, whereas a fractured aquifer is a further complex geological unit where groundwater exists in the pore spaces of rock matrix with negligible permeability. Thus, a classical porous system stores (storativity) and transports (transmissivity) the groundwater within a single entity (a geological unit having a single porosity), whereas a fractured aquifer with a marked heterogeneity between fracture and rock matrix stores groundwater within a low permeability rock matrix (i.e. in its inter-granular porosity), while the transport/migration of solutes occurs through the high permeability fractures, which basically act as conduits. Thus, at the very first instant, there is a fundamental difference between the dynamics of fluid flow within a porous/permeable groundwater aquifer and that through a fractured groundwater aquifer. During groundwater production from a fractured aquifer, high diffusivity causes a rapid pressure response at the large-scale fracture network, and eventually, creates a local-scale pressure difference between fracture and rock matrix at the scale of a single fracture resulting in fluid flow known as inter-porosity flow from matrix to fracture during the initial period, which was assumed to occur under pseudo-steady-state conditions by Barrenblatt *et al.*[1], and later, Warren and Root[2] provided a solution to the same. This pseudo-steady-state assumption was ignored later, and a transient fluid flow term from matrix to fracture was introduced by Kazemi[3] and de Swaan[4] and was solved numerically. As the pressure difference between fracture and matrix diminishes after a very large time period, fluid flow may result from a composite storativity of both fracture and rock matrix[5]. Thus, there is a fundamental difference between the two aquifers (porous and fractured aquifers) regarding groundwater storage and its conveyance mechanisms and in particular, groundwater flow in a fractured aquifer, deserves special attention over that of conventional porous medium aquifers, in order to maximize groundwater production, and subsequently to reduce the risks of failure of groundwater extraction projects associated with fractured aquifers. Further, the presence of high permeability fractures provides a preferential pathway to groundwater, which is stored in low-permeability rock matrix as against the random tortuous pathways associated with a conventional porous/permeable aquifer.

Until the last few years, the state-of-the-practice for fractured rock has been essentially the same as that of all contaminated sites. It had not been differentiated from that of unconsolidated-deposit sites. Technology evaluations, which are more specific to fractured rock are now emerging, but there is a time lag in the widespread communication of new research and applications to both the practising community and decision-makers. For example, research, development and technology evaluations have clearly conveyed that it is the fracture pathways with their associated matrix diffusion, rather than the complex discrete fracture network, which are important in assessing the contaminant migration in fractured media. In addition, the fractures must be hydraulically conductive and sufficiently interconnected to serve as a part of the pathway. Thus, locating these hydraulically significant, well-connected fractures becomes the ultimate challenge in characterizing a fractured reservoir. In this context, the objective of this study is to emphasize the fundamental differences associated with the conceptual modelling of fluid flow through a classical porous medium and a fractured reservoir. The study is limited to the concepts of fluid flow through a fractured reservoir with reference to that of a typical classical porous medium. In addition, the critical issues associated with the upscaling of fluid flow through fractured reservoirs are discussed.

For any two similar physical systems, for a given set of data, when the end results are marginally varying, while maintaining the fundamental pattern/trend the same, then, it is relatively easier to translate or extrapolate the characteristics of one physical system into another. However, when the end results vary significantly, while also not maintaining the fundamental pattern/trend, there is a significant risk or uncertainty associated with the translation/extrapolation on the characteristics of one physical system into another. In this context, the author has made an attempt to delineate the fundamental conceptual modelling differences between conventional classical porous medium and a fractured reservoir so that groundwater stakeholders would gain better insights while implementing management decisions associated with a fractured reservoir. The differences in conceptual modelling between classical porous medium and a fractured reservoir are provided in Table 1.

In the last few decades, both experiments at the laboratory scale and the efforts by numerical modellers have

Table 1. Differences in conceptual modelling between classical porous medium and fractured reservoir

Classical porous medium	Fractured reservoir
Characterized by primary porosity, which develops during the deposition of the sediments	Characterized by secondary porosity, which is developed by a diagenetic process subsequent to deposition
Intrinsic permeability is a function of square of mean grain size that developed during the deposition of the sediments.	Intrinsic permeability is a function of square of mean fracture aperture thickness that developed after its initial deposition
Does not provide a direct measure of pore size through which fluid flow occurs	Provides a direct measure of pore size through which fluid flow occurs
Conventional relation between intrinsic permeability and porosity such as Darcy's[9]; Slichter[10]; Kozeny[11] and Carmen[12]; relatively holds good	Conventional relation between intrinsic permeability and porosity does not hold good
Increase in (primary) porosity has a direct correlation with permeability enhancement	Increase in (secondary) porosity has no direct correlation with permeability enhancement as the fracture connectivity dictates the resultant enhancement in permeability
Storage and transmission of groundwater take place simultaneously within the pore spaces	Storage and transmission of groundwater remain separated; storage is associated with low-permeable rock matrix; transmission is associated with high-permeable fracture
Single continuum is sufficient	Needs multiple continuum as storage and transmission are associated with different geological units
Concept of REV holds good as a reasonable mean value can be deduced with a minimum variance	Deducing a reasonable REV remains nearly impossible as the heterogeneity keeps increasing with scale/volume
There is no interaction between fluid and solid either at the microscopic or at the macroscopic scale	Interaction between fluid and solid at the macroscopic-scale cannot be averaged over representative elementary volume (REV). There is a definite interaction (instantaneous/rate-limited) between the fluid (within the high permeable fracture) and the fluid within the low-permeable solid rock matrix
Application of no-slip boundary condition remains easy	Application of no-slip boundary condition at the fracture–matrix interface becomes complex as it needs to ensure continuity of fluid mass fluxes
Characterized by single flow regime	Characterized by two distinct flow regimes (one within the high permeable fracture and the other within the low-permeable rock-matrix)
Characteristic lengths of pore geometry do not vary significantly	Characteristic lengths of pore geometry (fracture) varies over several orders of magnitude; Thickness of fracture varies over tens/hundreds of microns; Width of fracture varies over tens/hundreds of centimetres; Length of fracture varies over tens/hundreds of meters; Difficult to conceptualize at a particular scale
Geometry of pore size/mean grain size does not have significant impact on the resultant flow regime	Geometry of pore size (fracture aperture thickness) does have a significant impact on the resultant flow regime IF Fracture thickness > 1000 microns THEN Complex flow regime within fracture ELSEIF Fracture thickness 10–1000 microns THEN Fluid flow is driven by + Δp and/or gravity ELSEIF Fracture thickness < 10 microns THEN Fluid flow is driven by – Δp (capillary effect)
Porosity corresponds to: (1) Total porosity; (2) Effective porosity (e.g. Sandstone reservoir porosity: 5–25%)	Porosity corresponds to 1. Porosity at the scale of a single fracture (100%) 2. Fracture porosity at a larger field scale (<10%) 3. Rock-matrix porosity (<5%) 4. Total porosity (1 – 25%) 5. Connected porosity

(*Contd*)

Table 1. (*Contd*)

Classical porous medium	Fractured reservoir
Intrinsic permeability is generally considered to be independent of time – along the line of steady-state Darcy's law	Intrinsic permeability mostly varies with time as the thickness of the fracture aperture is sensitive to (a) rock deformation kinetics; (b) thermo-elasticity and (c) poro-elasticity
Intrinsic permeability varies over several orders of magnitude over a large extent	Intrinsic permeability varies over several orders of magnitude over a very small distance @ F–M interface
Pressure gradient along the flow direction is critical	Pressure gradient normal to the flow direction (between fracture and rock-matrix) is very sensitive in addition to the pressure gradient along the flow direction within the fracture; Relatively difficult to deduce the resultant fluid flow direction
Residence time of fluid mass is not sensitive to mean fluid velocity (mean fluid velocity is around 1 m/d)	Residence time of fluid mass is extremely sensitive to mean fluid velocity (within the fracture); Decides the intensity of fluid mass transfer between fracture and matrix; (0.1 m/d and 100 m/d have completely different mean residence times and subsequently result in totally varying production rates) Existing models and/or commercial software packages do not consider mean fluid velocity in describing fluid mass transfer @ F–M interface in a typical dual-porosity system
Upscaling from laboratory to a larger field scale is straightforward	Upscaling from laboratory to a larger field scale is not straightforward as critical large-scale heterogeneities are missing with the laboratory-scale rock core samples; (100% sweeping with the laboratory-scale core samples has no relevance with the larger field-scale groundwater/hydrocarbon production efficiency)
Frictional resistance is encountered along the entire cross-sectional area normal to the flow direction	Frictional resistance is encountered only along the fracture walls
Driving force: Computation of net pressure force is straightforward $-\Delta pA\phi = -\frac{\Delta p}{\Delta l}A\Delta l\phi$	A = ? Fracture alone or F&M together?? ϕ = ? Fracture porosity/matrix porosity/total porosity?? Δp = ? Along flow direction alone?? (There exists a significant Δp normal to the flow direction)
Driving force: Computation of gravitational force is straightforward $F_g = mg\sin\theta = \rho A\Delta l\phi g\frac{\Delta z}{\Delta l}$	A = ? Fracture alone or F&M together?? ϕ = ? Fracture porosity/matrix porosity/total porosity?? ρ = ? For multi-phase fluid flow There is no direct means of finding the resultant gravitational force.
Resistive force: Forces opposing the fluid motion resulting from frictional drag is proportional to (a) specific discharge (determined by smooth distribution of pore velocities); (b) dynamic fluid viscosity and (c) total area of fluid-solid contact within the volume of fluid element	$F_{FR} = \left(\frac{1}{k}\right)(\mu)\left(\frac{Q}{A}\right)(A\Delta l\phi)$ ... Valid??? Pore velocity within the fracture is several orders of magnitude higher than that of rock matrix; and thus does not have a smooth distribution Total area of fluid–solid contact does not increase proportionately as the volume of rock-mass increases (specific surface area nearly remains the same); and hence, application of the above equation is not straightforward
Depth-wise variation in potential energy within the aquifer thickness is generally ignored	Characterized predominantly by vertical fractures, the gravitational head varies significantly as the potential energy of fluid parcels vary vertically with respect to a reference

(*Contd*)

Table 1. (*Contd*)

Classical porous medium	Fractured reservoir
Measurement of piezometric head has no complications associated with it	Since, the elastic energy stored by the fluid parcels within a low-permeable rock matrix; and within a high permeable fracture are not the same, the measurement of piezometric head becomes complex
Inertial forces always remain insignificant	Once the fluid mass comes out of low permeable rock matrix, the additional energy gained by the fluid parcels during its movement through high permeability fractures may not be insignificant, and subsequently might gain inertial forces as against what is observed in a classical porous medium
Simplified mean hydraulic conductivity can be applied	Since the direction of groundwater flow in a fractured media depends on strike and dip of fracture pattern, the requirement of a second order hydraulic conductivity tensor becomes crucial
Space- and time-independent permeability works well	Concepts of both scale-dependent and time-dependent permeability need to be looked at
The fluid of interest can be comfortably treated to be incompressible under normal circumstances	In a fractured reservoir, the amount of fluid expelled from a unit volume of rock consisting of both high permeable fracture and low permeable rock-matrix resulting from fluid expansion and reservoir compaction may not be uniform throughout the entire reservoir volume. This paves way for the consideration of density-dependent fluid mass resulting from variations in fluid mass over the respective volumes. Thus, treatment of fluid to be incompressible raises question in a fractured aquifer
Concepts of zero vertical acceleration (extended hydro-static principle for hydro-dynamics) and a near-zero vertical pressure/hydraulic gradient (Dupuit's approximation) in the vicinity of production wells may comfortably be applied	Concepts of zero vertical acceleration (extended hydro-static principle for hydro-dynamics) and a near-zero vertical pressure/hydraulic gradient (Dupuit's approximation) in the vicinity of production wells may not be directly applied in a fractured aquifer because the groundwater within a fractured aquifer is always driven by a relatively higher pressure differential than that of the porous reservoir
Groundwater fluid flux remains linearly proportional to potential gradient as the flow is assumed to be non-turbulent in the absence of inertial effects	Groundwater fluid flux may not always remain linearly proportional to potential gradient as the fluid flow may be associated with significant inertial effect or sometimes could be turbulent
The physical system tries to reach a steady-state condition after its initial perturbation/noises/fluctuations; and hence, the existing equation used to describe fluid flow through a typical porous medium pertaining to parabolic dominant diffusivity equation remains valid	The physical system does not try to reach a steady-state condition due to its associated heterogeneities and hence applying the same concept of parabolic dominant diffusivity equation may not be correct
The ratio that decides the advective/diffusive dominant nature of fluid flow always remains much less than one. $\text{Ratio} = \frac{c_\text{f}\,\mu Q}{2\pi kH} = \frac{c_\text{f}\,(P_\text{o} - P_\text{w})}{\ln(R_\text{o}/R_\text{w})}$	The ratio often becomes significant due to its associated heterogeneity; c_f might increase resulting from lateral normal/confining stress
Does not require any additional term other than parabolic dominant diffusivity equation $\frac{\partial^2 p}{\partial x^2} = \frac{\phi\mu(c_\text{f} + c_\text{m})}{k}\frac{\partial p}{\partial t}$	Requires an additional non-linear quadratic hyperbolic pressure-gradient term $\frac{\partial^2 p}{\partial x^2} + c_\text{f}\left(\frac{\partial p}{\partial x}\right)^2 = \frac{\phi\mu(c_\text{f} + c_\text{m})}{k}\frac{\partial p}{\partial t}$

been expended significantly to develop coupled fluid flow and solute transport equations in a highly heterogeneous groundwater aquifer system in order to quantify the mobility and spreading of solute concentrations. Such partial differential equations (PDEs) describing fluid flow and solute transport project the concerned processes at a macroscopic scale, which is the collective outcome over an ensemble of pores at the pore scale[6]. The purpose of developing such equations is to identify the key factors that may control groundwater flow and solute transport processes within an aquifer system at the pore scale, and eventually to incorporate those factors suitably at the macroscopic fluid flow and solute transport equations in order to simulate better remediation strategies. However, the critical scale-up issues from pore scale to field scale are often treated as afterthoughts because the groundwater engineers typically work either at the larger field scale or at the intermediate laboratory scale, but not at the pore scale due to the inherent complexities at this scale. As a result, local or pore-scale variations are neglected, and the mean values of constants and/or variables are deduced by assuming the given aquifer system to be more or less homogenous, and this is where depending on the geological complexities at the pore scale, groundwater production and concentration distribution estimates made at a relatively higher scale (either laboratory and/or field scale) remain either projected or dejected. This necessitates a good understanding of how the pore-scale physical processes are up-scaled to represent a continuum-scale mathematical expression in describing the fluid dynamics of a fractured aquifer. Such attempts are believed to provide a better insight on groundwater exploration and its associated groundwater pollution remediation schemes. For example, in a dual-permeability system, for multi-phase fluid flow, micro- or pore-scale dispersion of fluid can be expected within low-permeability rock matrix; Taylor's hydro-dynamic dispersion may be expected within high-permeability fracture; and in addition, macro-dispersion within the fracture can be expected resulting from differential advection between adjacent layers of extreme heterogeneities at a relatively larger scale. All the above three dispersions can be expected in a single fracture-matrix coupled system (dual-permeability/dual-porosity). Further, in the field scenario with a network of fractures, dispersion will also result from channelling[7,8] as well as the mixing at the fracture intersections or junctions. Thus, dominant processes such as dispersion resulting from preferential flow paths or channelling; and the dispersion resulting from fracture intersections are associated only with a larger field-scale problem; and not with the local-scale single fracture with matrix diffusion problem. Thus, it is not straightforward to upscale the problem of fluid flow through fractures from pore scale to field scale, and still requires much fundamental research before its successful field application.

The upscaling becomes further complex for multi-phase fluid flows. For example, the concept of relative permeability for different fluids needs a serious relook as there is nothing called relative permeability of oil or relative permeability of water based on Darcy's assumptions. This is because the so-called intrinsic permeability, from Darcy's perspective is a function of only rock property (mean grain size, d_{10} or d_{50}), in addition to the details on the pore geometry; and it does not depend on any fluid property. It is the hydraulic conductivity, or in general, the fluid conductivity, which is a function of reservoir as well as fluid properties (density and viscosity). However, it is conventionally followed to represent the mobility of fluids (water/air) at the pore scale in terms of its relative permeabilities, while the concept of average reservoir permeability is applied at a larger field scale. In this context, there is so far no theory that can directly upscale the pore-scale relative permeability to a larger field-scale average permeability. Thus, a good understanding of fluid flow through a fractured reservoir is required at different scales as well.

A detailed delineation of the conceptual modelling differences between classical porous medium and a fractured reservoir is presented. It can be concluded from this study that fluid flow through a fractured reservoir deserves special attention and its associated fluid flow analysis cannot be simplified using the conventional Darcy-based approach. In addition, it is also concluded that the upscaling issues associated with a classical porous medium cannot be directly applied to analyse fluid flow through a fractured reservoir.

Nomenclature

A	Cross-sectional area of aquifer system normal to flow (m^2)
c_f	Compressibility of fluid within fracture (Pa^{-1}).
c_m	Compressibility of fluid within rock-matrix (Pa^{-1})
g	Acceleration due to gravity (ms^{-2})
H	Aquifer thickness (m)
k	Absolute permeability (m^2)
m	Fluid mass (kg)
P_o	Effective pressure at effective radius (Pa)
P_w	Pressure at well bore (m)
Q	Fluid discharge (m^3)
R_o	Effective radius (m)
R_w	Radius of well-bore (m)
p	Aquifer pressure (Pa)
μ	Fluid viscosity (Pa.s)
ϕ	Porosity (dimensionless)
θ	Inclination of aquifer bed with reference to the reference plane
ρ	Fluid density (kg m^{-3})
Δl	Length along the flow direction (m)
Δz	Length along the vertical direction towards gravity (m)

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Delineation of groundwater saturation indicators and their distributions in the complex argillaceous geological units of Ezza north local government area of Ebonyi state, Nigeria

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Twelve vertical electrical soundings (VES) employing Schlumberger electrode configuration were carried out in parts of Ezza north local government area of Ebonyi state, Nigeria, where extraction of potable groundwater has posed challenges to the dwellers of the area who are currently relying on surface water sources and some scattered seasonal open wells that cause health problems. The present study was undertaken to determine the hydrogeological characteristics, indicators that predict groundwater potential of the study area. The study indicates that the aquifer resistivity ranges between 12 and 504 Ωm with an average value of 95.42 Ωm. Water resistivity ranges between 9.6 and 73.0 Ωm with an average of 26.34 Ωm. The aquifer thickness ranges from 34.1 to 214.7 m with an average of 71.97 m. Also, the formation factor varies between 1.25 and 6.9 with an average of 2.76. Porosity ranges between 5.34% and 29.47% with an average of 15.91%. Similarly, hydraulic conductivity ranges from 1.1645 to 38.0491 m/day, the average being 12.8312 m/day, and $K\sigma$ values range between 0.0023 and 3.1695 S/day with a mean value of 0.6273 S/day. Using surfer software package, contour distributions of geo-hydrodynamic properties were generated which show the distribution of the aquifer parameters in the study area. The distributions of these properties reflect the regions with high and low potential groundwater in the area. The diagnostic models and the inherent and intrinsic constants can be employed in quantitative prediction of groundwater potential in the adjoining regions of the study area which show similar hydrogeological properties.

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Keywords: Argillaceous geological units, groundwater potential, hydrogeological properties, vertical electrical sounding.

GROUNDWATER is the major source of water supply needed by humans for industrial, agricultural and domestic purposes. The natural quality is usually good, and it is resistant to even prolonged droughts[1]. Groundwater occurrence, storage and flow in a hard-rock terrain are controlled by the geology, geomorphology, divide and structure. Groundwater is usually contained within the weathered and tectonically induced geological features, fractured/fissured, sheared or jointed/faulted columns of rock units. These rock units are altered by geological processes. This alteration causes reduction in resistivity at depth of burial and a noticeable increase in secondary porosity, coefficient of permeability and permeability which are the major hydrodynamic properties[2] that serve as indicators and dependent factors that decide the distribution of units for groundwater accumulation, discharge and exploitation[3]. Within the last decade, hydrogeological information has been increasingly complemented with surface geophysical information that allows for more accurate images of aquifer systems[4]. Electrical resistivity method is versatile and economical for delineating the locations of productive aquifer sites and apparent thickness of the weathered zone, which is useful in siting boreholes in dense rocks. Layers in hard rocks characterized by thick fractures have high secondary porosity/permeability that connotes prolific geological units. The knowledge of electrical geophysical survey as an example can be used to assess aquifer potential of an area, thus, reducing the cases of failed boreholes. A detailed qualitative knowledge of water transmitting properties of an aquifer is crucial for successful groundwater development and management practices in an area. The efforts of government and non-governmental agencies in providing safe drinking water to some communities have recorded great successes, and have aided in not only solving the water scarcity problem, but also curbing the outbreaks of some waterborne diseases like cholera, diarrhoea, typhoid, guinea worm, etc. To avoid the cases of failure of some boreholes in the study area, there is need for a systematic study in order to delineate the potential groundwater