Natural Resources for Human Health
eISSN: 2583-1194

Original Research

Received 16 July 2026
Revised 17 Aug 2026
Accepted 03 Sep 2026

Natural Resources for Human Health 2026, Vol. 6 (20s): 343–352

KEYWORDS:
Lorem ipsum; dolor sit amet; consectetur; adipiscing elit; natural resources; phytochemistry.

Modelling of Subsurface Seepage Over Sloping Aquifer in Ditch Drain System Without Vertical Recharge

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ABSTRACT: The new analytical solution specifying water head and flow rate of ground water flow equation in downward sloping aquifer interacting with water streams of varying height is obtained by using inverse Laplace transform method. Principle aim of this article intend to depict unfolding of futuristic new analytical result for water head as well as volume velocity at both interfaces of downward inclined ditch drain aquifer system. Here new analytical expression of Boussinesq equation in its Linearization form representing transient ground water transport mechanism downhill inclined aquifer of unconfined type of meagre domain area is derived. It's connected to adjoining ditches of varying water level at both ends. Depth of water in ditches changes from initial altitude to final altitude and is approximated by exponential decay function of time.An analytical solution of governing ground water flow equation in linearization form with specified boundary conditions is solved by adopting integral transform methodology namely Laplace transform. By employing numerical methodology solution of correlated nonlinear version is deduced. Impact of linearization of nonlinear governing equation, recharge and slope of impermeable barrier on water variation in flow region of finite extent is elaborated taking aid of the various numerical. Innovations of head response over small changes in every hydraulic variables of unsteady fluid transport are effectuated through sensitivity analysis of transient flow. These solutions in turn utilized in prediction of water depth in relation with asymptotic conditions. Relation between flow rate and sloping angle of aquifer is explained graphically. In addition, sensitive analysis of hydraulic head, flow rate of different aquifer parameters is also explained. Ground water mound and its spatial location are computed using iterative scheme.

1. INTRODUCTION

Overuse of available water results into need for investigation related to its means of existence may be in form of surface or sub surface. Impact of man-made actions such as growth of agriculture component, which includes irrigation as well as use of chemicals for extraction of maximum crop yield, issue of sewage disposal due to industrial development, urbanization, draining of ground surface, excessive withdrawal of ground water, destruction of herbage, pollution etc. is point of attention seeking for researchers [1]. However, considering above issue together with sustainable development of environmental asset, it is necessary to understand that groundwater movement [26] process in depth so that adequate management and proper protection of natural resources can be achieved [2]-[4],[25].

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2. FORMULATION OF MATHEMATICAL MODEL

Figure 1 represents the schematic of the ditch drain inclined aquifer system [14].

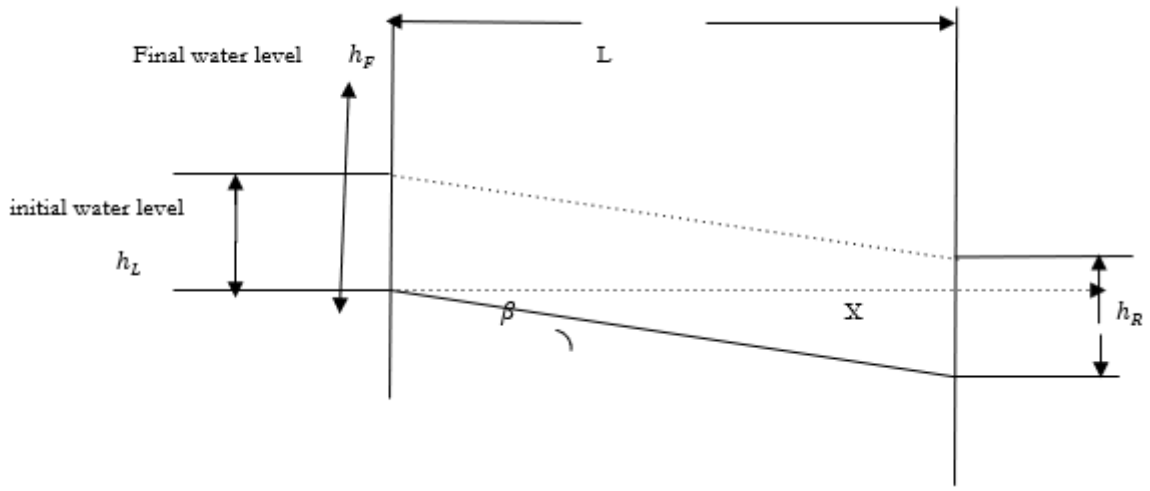


Figure 1 Schematic representation of ditch drain inclined aquifer system.

The hydrological model consists of an unconfined aquifer of finite domain [12]. The aquifer under consideration is of width L possesses property of homogeneity and isotropicity. Aquifer is interacting with water stream at h_L on the left boundary and h_R at right boundary [6]-[8]. Gradual change in water level to h_F be approximated by decaying function of time expressed exponentially [9]. Principles of hydraulics of unconfined groundwater movement over a slanting aquifer are built up using Darcy's equation [5], [10], [11] which follows the theory of conservation of momentum and mass balance equations [20], [22].The ground water movement in inclined aquifer is approximated by famous extended "Boussinesq equation (Chapman 1980), derived on basis of Dupuit –Forchheimer extension of fact that stream lines are almost parallel to inclined bed [21].

This assumption indicates that $dh \approx dx,$ i.e $h \ll dx$. governing ground water equation [23], [24] is expressed as

$$\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right) - tan\beta\frac{\partial h}{\partial x} = \frac{S}{Kcos^2\beta}\frac{\partial h}{\partial t} \quad (1)$$

Where conductivity is *K*, specific yield of aquifer *S* and measure of depth of water head in vertical direction from inclined bed $h(x,t),\ tan\beta$ is slope of considered slanting bed.

It is nonlinear, nonhomogeneous partial differential equation" representing 1-D, transient state ground water transport equation. initial condition (IC) and boundary condition (BC) are prescribed as follows. The initial condition is considered as :

$$h(x,t=0) = h_L - \frac{(h_L - h_R)x}{L} \quad (2)$$

The boundary constraints is expressed as

$$h(x=0,t>0) = h_F - (h_F - h_L)e^{-\lambda_1 t} \quad (3)$$

$$h(x=L,t>0) = h_R - (h_F - h_R)e^{-\lambda_2 t} \quad (4)$$

Here L is length of aquifer. λ_1 and λ_2 are positive constant which signifies rate at which srteam rises from h_L to h_F at left boundary and h_R to h_F at right boundary. Here h_F is final water level. Eq. (1) is second order nonlinear PDE which is analytically unsolvable due to its nonlinearity. Thus, to obtain approximate analytical solution linearization of above equation in terms of h^2 by addressing saturated mean or weighted mean $havg$ of height of water table is adopted (Marino 1973). However, $havg$

is obtained using successive approximations (Marino, 1973, 1974). Here $havg$ is given by $havg=h_i + h_t/2$ where h_i represents initial water table height and at any instant t, water table height is h_t. Value of h is approximated at end of t. ground water movement in inclined aquifer is approximated by famous Boussinesq equation(Childs 1971) which is nonlinear equation is presented by [24]

$$\frac{\partial^2 h}{\partial x^2} - \frac{tan\beta}{havg}\frac{\partial h}{\partial x} = \frac{S}{K\ havg\ cos^2\beta}\frac{\partial h}{\partial t} \quad (5)$$

Where hydraulic conductivity is *K*, specific yield of aquifer *S* and measure of depth of water head in vertical direction from inclined bed $h(x,t),\ tan\beta$ is slope of slanting bed. Introducing dimensionless variables as

$$H = \frac{(h-h_R)+(h_L-h_R)}{L}, X = \frac{x}{L}, \tau = \frac{K\ havg\ cos^2\beta}{SL^2}t \quad (6)$$

Using these variables equation (6) is transformed as

$$\frac{\partial^2 H}{\partial X^2} - 2\alpha\frac{\partial H}{\partial X} = \frac{\partial H}{\partial \tau} \quad (7)$$

Where $\alpha = (L\ tan\beta)/(2\ havg)$. Thus, with above-mentioned dimensionless variable and simplifying further, initial condition and boundary condition is transformed as follows:

$$H(X, \tau = 0) = K_1(2 - X) \quad (8)$$

$$H(X = 0, \tau) = K_2\left(1 - e^{-\lambda_1 t}\right) + 2K_1 \quad (9)$$

$$H(X = 1, \tau) = K_3\left(1 - e^{-\lambda_2 t}\right) + K_1 \quad (10)$$

Denoting

$$\lambda_1' = \frac{SL^2}{K\ havg\ cos^2\beta}\lambda_1 \quad (11)$$

$$\lambda_2' = \frac{SL^2}{K\ havg\ cos^2\beta}\lambda_2 \quad (12)$$

Applying Laplace transform to equation (7)

$$\frac{d^2\underline{H}}{dX^2} - 2\alpha\frac{d\underline{H}}{dX} - s\underline{H}(X,s) + \underline{H}(X, \tau = 0) = -K_1(2 - X) \quad (13)$$

Equation (13) can be solved by ordinary methods. Roots of auxiliary equation are $\alpha + \sqrt{\alpha^2 + s}$ and $\alpha - \sqrt{\alpha^2 + s}$

$$\underline{H}(X,s) = e^{\alpha X}\left(AcoshX\sqrt{\alpha^2 + s} + B\ coshX\sqrt{\alpha^2 + s}\right) + \frac{K_1(2-X)}{s} + \frac{2\alpha K_1}{s^2} \quad (14)$$

A, B represents arbitrary constants. By applying Laplace transform over prescribed boundary conditions above values are estimated. The resultant is expressed as

$$\underline{H}(X,s) = \frac{e^{\alpha X}\left(\frac{K_2\lambda_1'}{s(s+\lambda_1')} - \frac{2\alpha K_1}{s^2}\right)sinhsinh\,(1-x)\sqrt{\alpha^2+s}}{sinh\sqrt{\alpha^2+s}} +$$

$$\frac{e^{-\alpha(X-1)}\left(\frac{K_3\lambda_2'}{s(s+\lambda_2')} - \frac{2\alpha K_1}{s^2}\right)sinhx\sqrt{\alpha^2+s}}{sinh\sqrt{\alpha^2+s}} + \frac{K_1(2-X)}{s} + \frac{2\alpha K_1}{s^2} \quad (15)$$

By applying calculus of residue technique inverse Laplace transformed form expression of (15) is obtained.

3. EXPRESSION FOR WATER HEAD PROFILES

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$$H(X,\tau) = e^{\alpha X}\left\{\frac{K_2 sinhsinh\,(1-X)\sqrt{\alpha^2-\lambda_1'}\,(1-e^{-\lambda_1'\tau})}{sinsin\,h\sqrt{\alpha^2-\lambda_1'}} + \sum_{n=1}^{\infty} \frac{K_2 2n\pi sinsin\, n\pi X\left\{1-e^{-(\alpha^2+n^2\pi^2)\tau}\right\}}{\left\{1-\frac{(\alpha^2+n^2\pi^2)}{\lambda_1'}\right\}(\alpha^2+n^2\pi^2)} - 2\alpha K_1\tau\frac{sinhsinh\,(1-X)\,\alpha}{sinsin\,h\alpha} + 2\alpha K_1\sum_{n=1}^{\infty} \frac{2n\pi sinsin\, n\pi X\left\{1-e^{-(\alpha^2+n^2\pi^2)\tau}\right\}}{(\alpha^2+n^2\pi^2)^2}\right\} + e^{-\alpha(1-X)}\left\{\frac{K_3 sinhsinh\,X\sqrt{\alpha^2-\lambda_2'}\,(1-e^{-\lambda_2'\tau})}{sinsin\,h\sqrt{\alpha^2-\lambda_2'}} - \sum_{n=1}^{\infty} \frac{(-1)^n K_3\, 2n\pi sinsin\, n\pi X\left[1-e^{-(\alpha^2+n^2\pi^2)\tau}\right]}{\left[1-\frac{(\alpha^2+n^2\pi^2)}{\lambda_2'}\right][\alpha^2+n^2\pi^2]} - 2\alpha K_1\tau\frac{sinhsinh\,X\,\alpha}{sinsin\,h\alpha} - 2\alpha K_1\sum_{n=1}^{\infty} \frac{(-1)^n 2n\pi sinsin\, n\pi X\left\{1-e^{-(\alpha^2+n^2\pi^2)\tau}\right\}}{[\alpha^2+n^2\pi^2]^2}\right\} + K_1(2-X) + 2\alpha K_1\tau \qquad (16)$$

The equation (16) represents analytical expression for height of water table in unconfined inclined aquifer as result of seepage from connecting ditches [13] and [19].

4. FLOW RATES AT THE INTERFACE

Chapman (1980) obtained unsteady flow rate defined per unit area of aquifer based on Dupuit-Forchheimer assumption [23] is stated as

$$q(x,t) = -Kh\beta\left(\frac{\partial h}{\partial x} - tan\,tan\,\beta\right) \qquad (17)$$

The expression for dimensionless flow rate or seepage rate is

$$Q(x,\tau) = -\left\{H(X,\tau) - K_1 + \frac{h_R}{L}\right\}\left\{\left(\frac{\partial H}{\partial X}\right) - tan\,tan\,\beta\right\}\beta \qquad (18)$$

The expression at left and right interfaces for discharge rate can be evaluated by using partial derivatives of H with respect to X at $X = 0$ and 1

$$\frac{\partial H}{\partial X} = e^{\alpha X}\{\mu_1\} + \alpha e^{\alpha X}\{\mu_2\} + e^{-\alpha(1-X)}\{\mu_3\} + \alpha e^{-\alpha(1-X)}\{\mu_4\} - K_1 \qquad (19)$$

Where

$$\mu_1 = \left\{\frac{-K_2\sqrt{\alpha^2-\lambda_1'}\,cosh(1-X)\sqrt{\alpha^2-\lambda_1'}\left(1-e^{-\lambda_1'\tau}\right)}{sinh\sqrt{\alpha^2-\lambda_1'}} + \sum_{n=1}^{\infty} \frac{K_2 n\pi 2n\pi coscos\, n\pi X\left\{1-e^{-(\alpha^2+n^2\pi^2)\tau}\right\}}{\left\{1-\frac{(\alpha^2+n^2\pi^2)}{\lambda_1'}\right\}(\alpha^2+n^2\pi^2)} + \alpha.2\alpha K_1\frac{coshcosh\,(1-X)\,\alpha\,\tau}{sinsin\,h\alpha} + 2\alpha K_1\sum_{n=1}^{\infty} \frac{\left\{1-e^{-(\alpha^2+n^2\pi^2)\tau}\right\}}{(\alpha^2+n^2\pi^2)^2}\right\} \qquad (19\text{ a})$$

$$\mu_2 = \left\{\frac{K_2 sinhsinh\,(1-X)\sqrt{\alpha^2-\lambda_1'}\left(1-e^{-\lambda_1'\tau}\right)}{sinhK_2\sqrt{\alpha^2-\lambda_1'}} + \sum_{n=1}^{\infty} \frac{K_2 2n\pi sinsin\, n\pi X\left\{1-e^{-(\alpha^2+n^2\pi^2)\tau}\right\}}{\left\{1-\frac{(\alpha^2+n^2\pi^2)}{\lambda_1'}\right\}(\alpha^2+n^2\pi^2)} - 2\alpha K_1\frac{sinhsinh\,(1-X)\,\alpha\,\tau}{sinsin\,h\alpha} + 2\alpha K_1\sum_{n=1}^{\infty} \frac{2n\pi sinsin\, n\pi X\left\{1-e^{-(\alpha^2+n^2\pi^2)\tau}\right\}}{(\alpha^2+n^2\pi^2)^2}\right\} \qquad (19\text{ b})$$

$$\mu_3 = \left\{\frac{K_3 cosh\sqrt{\alpha^2-\lambda_2'}\,cosh\,X\sqrt{\alpha^2-\lambda_2'}\,(1-e^{-\lambda_2'\tau})}{sinsin\,h\sqrt{\alpha^2-\lambda_2'}} - \sum_{n=1}^{\infty} \frac{(-1)^n K_3\, n\pi.2n\pi coscos\, n\pi X\left[1-e^{-(\alpha^2+n^2\pi^2)\tau}\right]}{\left[1-\frac{(\alpha^2+n^2\pi^2)}{\lambda_2'}\right][\alpha^2+n^2\pi^2]} - \alpha.2\alpha K_1\frac{coshcosh\,X\,\alpha\,\tau}{sinsin\,h\alpha} - 2\alpha K_1\sum_{n=1}^{\infty} \frac{(-1)^n n\pi.2n\pi coscos\, n\pi X\left\{1-e^{-(\alpha^2+n^2\pi^2)\tau}\right\}}{[\alpha^2+n^2\pi^2]^2}\right\} \qquad (19\text{ c})$$

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$$\mu_4 = \left\{ \frac{K_3 sinhsinh\, X\sqrt{\alpha^2-\lambda_2'}\,(1-e^{-\lambda_2'\tau})}{sinsin\, h\sqrt{\alpha^2-\lambda_2'}} - \sum_{n=1}^{\infty} \frac{(-1)^n K_3\, 2n\pi sinsin\, n\pi X\left[1-e^{-(\alpha^2+n^2\pi^2)\tau}\right]}{\left[1-\frac{(\alpha^2+n^2\pi^2)}{\lambda_2'}\right][\alpha^2+n^2\pi^2]} - 2\alpha K_1 \frac{sinhsinh\, X\,\alpha\,\tau}{sinsin\, h\alpha} - 2\alpha K_1 \sum_{n=1}^{\infty} \frac{(-1)^n 2n\pi sinsin\, n\pi X\left\{1-e^{-(\alpha^2+n^2\pi^2)\tau}\right\}}{[\alpha^2+n^2\pi^2]^2} \right\} \quad (19\ d)$$

5. DISCUSSION OF RESULTS

Numerical examples explained here demonstrates results deduced from the above study. Values of aquifer parameter used in example are represented in Table 1.

Table 1: Values of aquifer parameters

Parameter	Value
K	2.5
S	0.2
L	100 m
h_L	10 m
h_R	7 m
h_F	12 m

Fluctuations of water table corresponding to under consideration 3^0 Downhill inclined aquifer with λ_1= 0.5 d^{-1} and λ_2 = 0.8 d^{-1} is shown in Figure 2 for various values of dimensionless time τ.

Corresponding numerical values are given in Table 2.

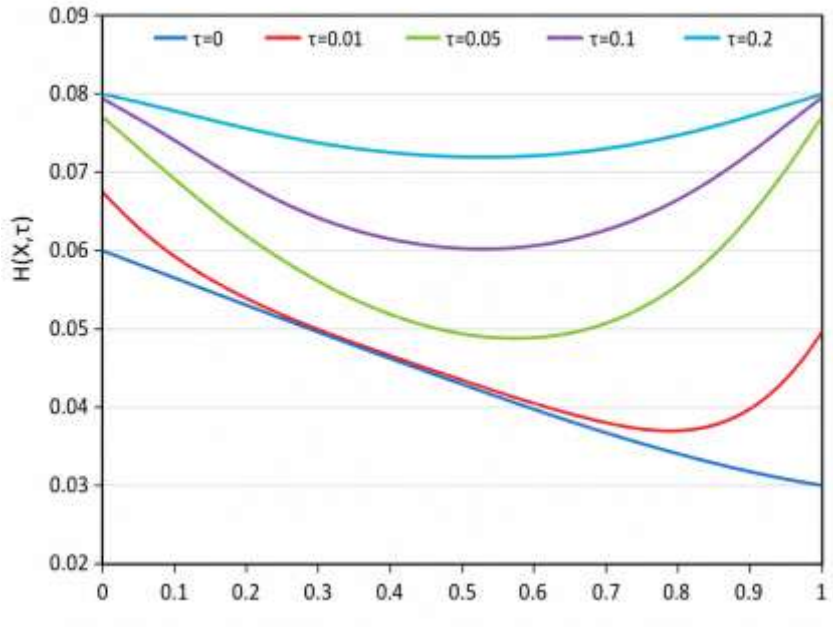


Figure 2: Dimensionless water head depth corresponding to 3^0 downhill inclined aquifer.

Water head in aquifer rises with time; however, rise in middle part of aquifer is less than that of left end and right end of aquifer [15] an [16]. As time progresses, water head profiles attain steady-state value.

Table 2: Estimates representing dimensionless head height corresponding to 3^0 Downhill inclined aquifer

X	$\tau = 0$	$\tau = 0.01$	$\tau = 0.05$	$\tau = 0.1$	$\tau = 0.2$
0	0.06	0.07103	0.07964	0.07999	0.08
0.05	0.0585	0.06525	0.07593	0.07783	0.07922
0.1	0.057	0.06086	0.0722	0.07561	0.07841
0.15	0.0555	0.0576	0.06858	0.07339	0.0776
0.2	0.054	0.05513	0.06513	0.07122	0.07681
0.25	0.0525	0.05316	0.06193	0.06916	0.07606
0.3	0.051	0.05144	0.05905	0.06727	0.07538
0.35	0.0495	0.04986	0.05653	0.06561	0.07477
0.4	0.048	0.04833	0.05442	0.06423	0.07427
0.45	0.0465	0.04682	0.05276	0.06318	0.07389
0.5	0.045	0.04532	0.05161	0.06251	0.07365
0.55	0.0435	0.04382	0.05102	0.06226	0.07356
0.6	0.042	0.04235	0.05107	0.06245	0.07364
0.65	0.0405	0.04093	0.05183	0.06311	0.07388
0.7	0.039	0.03967	0.05337	0.06424	0.0743
0.75	0.0375	0.03879	0.05575	0.06585	0.07488
0.8	0.036	0.03876	0.05899	0.06792	0.07563
0.85	0.0345	0.04033	0.06311	0.07041	0.07654
0.9	0.033	0.04461	0.06805	0.0733	0.07758
0.95	0.0315	0.05288	0.0737	0.07652	0.07874
1	0.03	0.06615	0.07992	0.08	0.08

Profile of water head with same parameters in 3 degree upward sloping aquifer is shown in Figure 3.

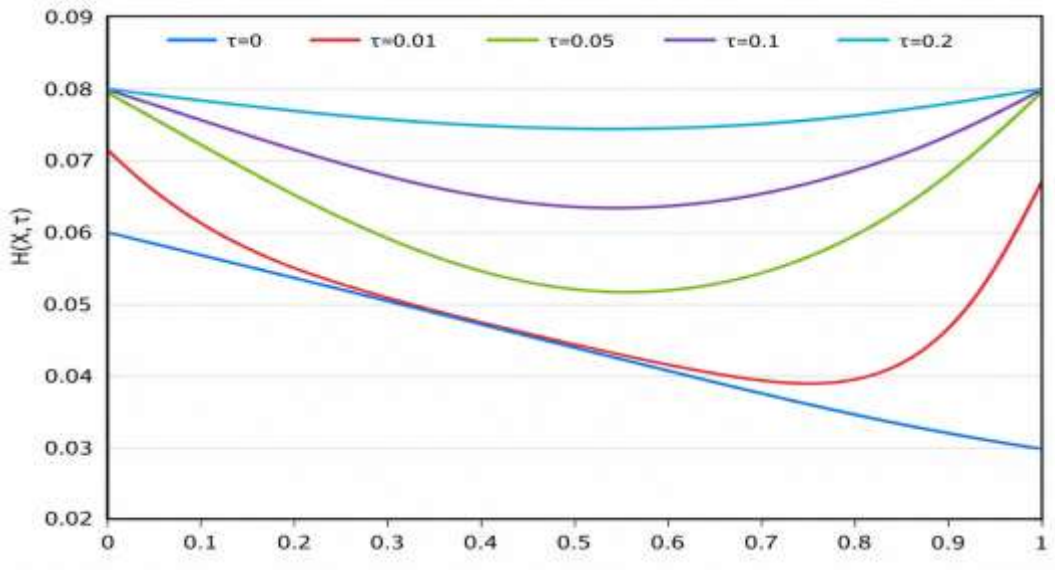


Figure 3: Dimensionless water head height in 3 degree upward sloping aquifer

Corresponding numerical values are given in Table 3. Stream-stage variation also influences rise in water table.

Table 3: Numerical values of dimensionless water head height in 3 degree upward sloping aquifer

X	$\tau = 0$	$\tau = 0.01$	$\tau = 0.05$	$\tau = 0.1$	$\tau = 0.2$
0	0.06	0.07103	0.07968	0.07999	0.08
0.05	0.0585	0.06463	0.07735	0.07898	0.07974
0.1	0.057	0.06005	0.07478	0.07781	0.07943
0.15	0.0555	0.05679	0.07204	0.07651	0.07908
0.2	0.054	0.05438	0.06921	0.07509	0.07871
0.25	0.0525	0.05246	0.06637	0.07358	0.0783
0.3	0.051	0.05078	0.0636	0.07203	0.07788
0.35	0.0495	0.04922	0.06097	0.07047	0.07745
0.4	0.048	0.04769	0.05856	0.06897	0.07702
0.45	0.0465	0.04619	0.05643	0.06757	0.07662
0.5	0.045	0.04469	0.05465	0.06635	0.07627
0.55	0.0435	0.0432	0.05329	0.06538	0.07598
0.6	0.042	0.04174	0.05245	0.06472	0.07577

0.65	0.0405	0.04035	0.05223	0.06446	0.07567
0.7	0.039	0.03918	0.05277	0.06468	0.07571
0.75	0.0375	0.03847	0.0542	0.06544	0.07591
0.8	0.036	0.03874	0.05668	0.06684	0.07628
0.85	0.0345	0.04073	0.06036	0.06893	0.07687
0.9	0.033	0.04542	0.0654	0.07179	0.07767
0.95	0.0315	0.05374	0.07189	0.07547	0.07871
1	0.03	0.06615	0.07993	0.08	0.08

Figure 4 represents fluctuations in water table in 3 degree downward sloping aquifer when $\lambda_1 = 0.2$ d^{-1} and $\lambda_2 = 0.3$ d^{-1}. Whereas table 4 displays correlated tabulated numerical estimates. Data exhibited in graph depicts slow rise in stream-stage affects overall growth of water table, as profile settle at lower value [17]-[18]. However, steady-state profiles of water head are irrespective of rate at which water in streams rise.

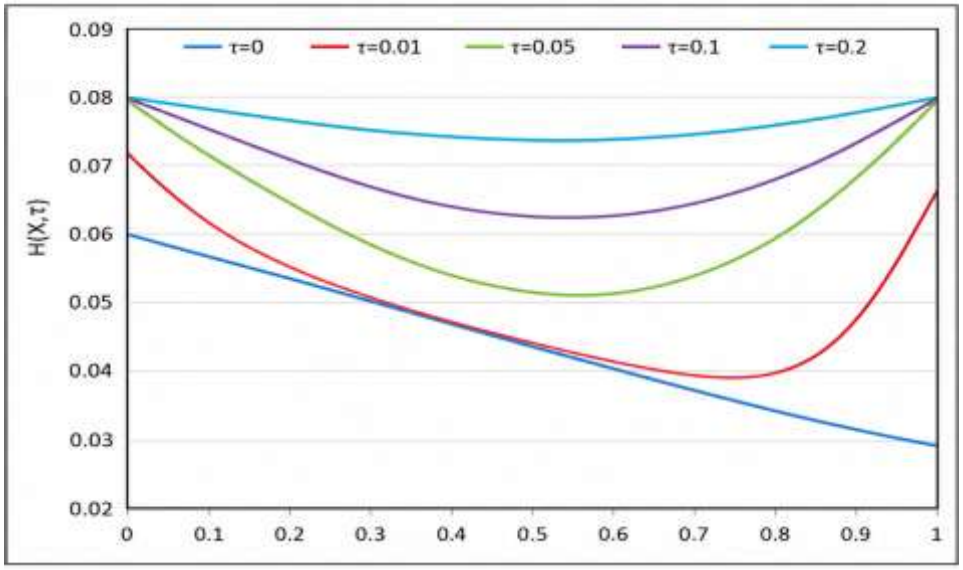


Figure 4: Dimensionless water head height in 3 degree upward sloping aquifer for slow rising stream-stage

Table 4: Estimates representing dimensionless head height corresponding to 3^0 downhill inclined aquifer under slow rising stream

X	$\tau = 0$	$\tau = 0.01$	$\tau = 0.05$	$\tau = 0.1$	$\tau = 0.2$
0	0.06	0.06549	0.07598	0.07919	0.07997
0.05	0.0585	0.06181	0.07218	0.07665	0.07903

0.1	0.057	0.05892	0.06856	0.07409	0.07806
0.15	0.0555	0.0566	0.06517	0.07158	0.0771
0.2	0.054	0.05467	0.06205	0.06917	0.07616
0.25	0.0525	0.05296	0.05921	0.06692	0.07527
0.3	0.051	0.05137	0.05667	0.06488	0.07445
0.35	0.0495	0.04983	0.05443	0.06309	0.07374
0.4	0.048	0.04832	0.0525	0.06162	0.07315
0.45	0.0465	0.04682	0.05091	0.06051	0.07271
0.5	0.045	0.04532	0.04968	0.05979	0.07244
0.55	0.0435	0.04382	0.04888	0.05952	0.07234
0.6	0.042	0.04233	0.04857	0.05972	0.07243
0.65	0.0405	0.04086	0.04884	0.06042	0.07273
0.7	0.039	0.03946	0.04981	0.06165	0.07323
0.75	0.0375	0.03824	0.05157	0.06341	0.07393
0.8	0.036	0.0374	0.05425	0.0657	0.07482
0.85	0.0345	0.03733	0.05795	0.06851	0.07589
0.9	0.033	0.03867	0.06272	0.0718	0.07713
0.95	0.0315	0.04226	0.06858	0.07552	0.07851
1	0.03	0.0491	0.07549	0.07959	0.08

6. CONCLUSION

New analytical solutions are established for the estimation of water table variations and discharge rate in an archetypical ditch-drain aquifer system underlain by an inclined impermeable bed. The solutions are obtained from Boussinesq equation, the validity of whose linearization has been critically assessed by a numerical scheme. The solutions developed here have the capability of predicting spatio-temporal variations in water table and discharge rate at either ends of the aquifer. The results developed here can be used as test cases for numerical modelling and guideline for experimental work.

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