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Full Length Research Paper

An economic assessment of the impact of information and communications technology (ICT) on performance indicators of water resource management in West Africa: A suggested strategy for avoiding the eminent international water wars

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Using data from 16 West African countries, this paper examines the links between Per Capita Income, Trade and Financial indicators, Education and Freedom indicators. Others are internet users, broadband and mobile cell phone subscribers. Meanwhile fresh water supply (which is assumed as a bench mark public sector-led water resource management performance indicators) and access to safe drinking water (a bench mark private sector-led water resource management performance indicators) represents indicators of water resources management. The results show that income, information and communications technology (ICT) and government trade policies influence the efficient management of cross-country water resource. Freedom indicators strongly affect water resource management performance indicators (WRMPI). Internet Users, Broadband Subscribers, and Mobile cell phones subscribers have a positive association with WRMPI. However, contrary to wide spread expectations, education does not influence WRMPI. In areas where water resource management performance indicators of safe drinking water exhibited strong correlation are: Secondary school enrollment rate (0.57), fresh water supply with consumer price inflation (0.78) and a fair correlation of safe drinking water with corruption index.

Key words: Information and communications technology (ICT), resource management, safe drinking water.

INTRODUCTION

The diffusion of information communication technology has led to greater integration of economies around the world. An assessment of cross-country data however, reveals potential danger, as countries will definitely engage each other in water wars in the nearest future (Sule, 2003). It is common sense that with an increase in population, there will be a corresponding rise in the demand for fresh and safe drinking water.

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Consequently, this water related crisis will fuel the tendency for governments of countries to strategise on ways to control water sources. There is a growing body of literature focusing on ICT tools, water resource management and its impact on the economy. The arguments presented by Swinford et al. (2007), Krantz and Kifferstein (2009), Shirley (2006) and Ribando et al. (1999) reveals that indicators of efficient water resource management has a significant positive impact on the gross domestic product (GDP) growth in varying degrees across the countries on the continent. Using simple descriptive statistics based on questionnaires, numerous studies have shown that ICT tools have greatly contributed to greater strategic management of the nations' water resources without necessarily escalating cross boarder tension (Van et al., 2003; Komsky et al., 2001; Swinford et al., 2007).

Based on these findings, it is plausible that in the era of the New Economy, new channels for assessing and improving water resource management is possible. Such a window may allow West African countries to fast track good governance in terms of cross country water resource and ensure more sustainable development. Thus it is important to conduct an economic assessment of the structural changes ushered in by the "New Economy" – described by Jorgenson (2007) as a mantra for faster, better and cheaper alternative systems and machines.

There is obviously a greater number of works on water economics, ICT and water resources and quality. Relatively, smaller works has been undertaken to understand in statistical terms, the impact of ICT and certain socio-economic indicators on water resources management (WRM), particularly in West African countries. For instance, Valipour (2014a) attempted to profile agriculture water management and identified platforms for this purpose. In focusing solely on West African economies, this work can add to the body of literature by addressing this salient issue. First, is an econometric assessment of the certain ICT and socio economic variables on WRM. Secondly, the direction of causality will be formally ascertained. Thirdly, other variables such as policy, civic society, and freedom can be crucial in this context.

Many papers have pointed out that water is plausible due to increasing demand on earth's water resources. More so, some other researchers have emphasized the catalysing role of citizen participation in the increased deployment of ICT (Heintz, 2004; Lagerskog, 2008; Moorhouse and Ellif, 2002; Jamieson and Fedra, 1996; Guimares et al., 2003; European Union, 2000; CET, 2003; Alder and Jacobs, 2000; Arnstein, 1969; CEC, 2001a). They argue that the increased participation of the public (through extensive use and deployment of ICT leads to more effective management of water resources as it broadens and guarantee speed of access to information and knowledge that can result in greater participation of people in decision making processes.

In Baliamoune-Lutz (2003)'s words "…a reduction in information asymmetry that enhances efficiency and access to knowledge for all would prevent one party from monopolizing opportunities … and at the same time allow participation of previously excluded groups." However, the role of ICT in effectively combating cross-border challenges is yet to be empirically tested using data from West African countries. There are ambiguous conclusions concerning the link between some economic variables, ICT and water resources challenges in West African countries. Another challenging concern is the issue of causality. Can efficiently deployed ICT resources coupled with effective policy engineering on government's part and an engaging civil society forestall the emergence of cross country water wars? This is so because Valipour (2013) argued that water management is one of the most effective parameters towards achieving sustainable development in the world.

This paper examines the relationship between water resources management indicators, ICT and a set of time tested macroeconomic and policy variables for a sample of 53 African countries. These countries are listed in Appendix 1. Specifically, the paper explores the nature and direction of the links between WRM indicators and per capita income, trade and financial liberalization, literacy and education and freedom indicators including economic freedom, liberties and political rights. The fresh water supply, and safe drinking water are used as indicators of WRM bench marks in a cross country these two basis performance indicators as well as the set of macroeconomic and policy variables mentioned above.

DATA AND METHODOLOGY

In the words of Jorgenson and Stiroh (2002) "a new economy" is the mantra for technological and structural changes as individuals (once excluded from mainstream events) capitalize on new technologies, new opportunities and national investments in computing, information and communication technologies. Quah (2001) includes intellectual asset, electronic libraries and databases and biotechnology (Carbon – based libraries and database). On the other hand, Swinford et al. (2007) identified broadly some ICT-oriented performance indicators for water resource management: measures of openness, civil participation, accountability and trust. This paper focuses only on: WRM performance indicators (WRMPI) such as fresh water supply measured in KM^3/Yr across countries and the availability of safe drinking water, ICT indicators such as mobile phone subscribers per 100 inhabitants, broadband subscription per 10,000 inhabitants and Internet users per 10,000 inhabitant. The data on these variables are for the periods of 2007 unless otherwise stated, are taken from the website of World Water.Org. Fresh water supply may be viewed as an indicator of the state to control fresh water resources within its political boundary, while safe drinking water, the second performance indicator measures the access to bottle and sachet water usually private controlled. The model proposed is:

$$WRMPI_i = \alpha + g\prod + \varepsilon_i \quad (1)$$

Where the vector $\prod$ contains all indicators. That is: $WRMPI_i$ = Fresh Water Supply/ Safe Drinking Water.

Table 1. Correlation among ICT-water resource management performance indicators.

Variables	SDW/POP	In PCI	BS	IPI	FWS(KM^3/YR)	SER	PR	HDI	CPI	CI	POP	SDW
SDW/POP	1.000											
In PCI	0.212	1.000										
BS	0.382**	0,238	1.000									
IPI	0.656**	0.311*	0.408**	1.000								
FWS(KM^3/YR)	-0.138	-0.052	0.101	-0.221	1.000							
SER	0.306*	0.446**	0.461**	0.669**	-0.304*	1.000						
PR	0.215	0.120	0.059	-0.166	0.113	-0.170	1.000					
HDI	0.314*	0.072	-0.120	-0.456**	0.225	-0.362**	-0.057	1.000				
CPI	-0.076	-0.182	0.086	-0.148	0.776**	-0.175	0.033	0.164	1.000			
CI	0.210	0.386**	0.306*	0.470**	0.301*	0.496**	-0.387	0.015	-0.163	1.000		
POP	-0.211	-0.053	0.323*	0.010	0.301*	0.085	0.076	0.167	-0.057	0.057	1.000	
SDW	0.524**	0.305*	0.382***	0.524**	-0.322*	0.569**	0.275*	-0.362**	-0.177	0.473**	-0.127	1.000

*indicates significance at 0.1, ** indicates significance at 0.05,*** indicates significance at 0.01. Sources: Author's Computation, ICT indicators are from International Telecommunication Union Website (2008); indexes for Civil Liberties and Political Rights are Freedom House website (2008); Economic Freedom index is from the Heritage Foundation website (2008); Education Index is from UNDP – Human Development Report 2008; Standard and Poor's Global Water Index website (2008); all other variables are from World Development Indicators CD-ROM (World Bank, 2008).

I = per capita income, F = Index of Economic Freedom, R = Political Rights, L = Civil Liberties, SR = Secondary School Enrollment Rate, HI = Human Development Index, CI = Corruption Index, CPI = Consumer Price Index, BS=Broadband Subscribers, IU=Internet Users, MCS=Mobile Cell Phone Subscribers.

Model (1) represents an equation to be estimated and the assumption of FWS and SDW as performance assessment indicators is fairly standard and plausible on both theoretical and empirical grounds (Swinford et al., 2007; Krantz and Kifferstein, 2009; Shirley, 2006; Ribando et al.,1999). In general, the association between WRMP indicators and income is expected to be very weak. This seems to be the case given the significant correlation of 0.31 between access to safe drinking water (Sachet/Bottle Water) and natural logarithm of per capita income. It is quite expected that income is not statistically significant with FWS as this is a natural resource endowment that has no link to income status of an economy. It is still not significant to the ratio of Fresh Water Supply and Safe Drinking Water to population (Table 1). However, in areas where water resource management performance indicators of safe drinking water are exhibited, strong correlation are: Secondary school enrollment rate (0.57), fresh water supply with consumer price inflation (0.78) and a fair correlation of safe drinking water with corruption index.

WRM performance indicator safe drinking water corrects strongly with internet penetration index (0.52) but had a weak one though statistically too with broadband subscriber (0.38).

This paper also uses freedom indicator namely Index of Economic Freedom published by the Heritage Foundation. It scores an average score of 10 indexes measured on a one to five scale with 5 indicating the lowest level of economic freedom. These variables also assess trade policy, monetary policy, capital flows and foreign investment, wage and price control, banking and bureaucracy, government intervention in the economy and the fiscal burden of the government (taxes and expenditure). Others are political rights and civil liberties. This paper is adopting approaches by Norris (2000) and Baliamoune-Lutz (2003). These two indexes are published by Freedom House and measured on a one to one seven scale with 7 indicating lowest degree of freedom. The correlation safe drinking water with Liberties and political rights are (SDW: PR = -0.28, and SDW: CL = -0.36). The signs on the coefficient are negative, implying that a fall in the index (an improvement) is associated with an increase in access to SDW. In discussing other policy variables such as financial liberalization and international trade variables, Baliamoune-Lutz (2003) defined financial deepening as the ratio of broad money (M2) to GDP is used as a proxy for financial liberalization. Eke (2007) and Baliamoune-Lutz (2003) argued that with increased financial deepening banks strive to make information available to their customer and generate additional income from service charge. Therefore increased deepening would empower consumers more. Many economic opportunities would be explored. This implies that financial deepening should spur establishment of more bottling water firms, civic action initiatives on better water management policy and strategies.

The correlation coefficient in Table 1 shows that there a negative (though not statistically significant correlation between financial liberation core WRM performance indicators. (FWS: FL = -0.042; SDW: FL = -0.11). This discovery could be that since (M2) and GDP were measured in dollars terms, most West African countries have experience stiff decline (in dollar terms) over the years due to weakening exchange rates. The sensitivity of these countries water industry to trends in the international market was assessed using the net financial flows (NFF),

Table 2. An Economic assessment of the impact of ICT on performance indicators of water resource management in west africa dependent variable: FWS KM^3/Yr.

Equations	1	2	3	4
Number of observations	53	53	53	53
Adjusted R^2	0.651	0.160	0.129	0.661
Constant	35.366	23.008	-24.260	52.252
PCI	0.0005(0.009)	0.0003(0.014)	0.0009(0.013)	0.0007(0.009)
IEF	0.331(0.290)	-0.0004(0.435)	-0.0002(0.432)	0.349(0.301)
PR	10.665(23.643)			0.588(25.055)
CL	-8.000(31.381)	18.669(21.895)	23.364(19.707)	-4.781(32.682)
SER	-1.257(0.911)	-1.208(1.396)	-1.481(1.239)	-1.642(1.072)
HDI	0.009(0.510)	0.706(0.776)	0.575(0.720)	0.0002(0.542)
CI	-3.839(28.718)	-19.157(44.073)		-4.780(31.906)
CPI	2.207(0.278)			2.157(0.295)
NFF			0.0005(0.012)	0.0005(0.009)
BS				0.0002(0.292)
IU				-0.0004(0.018)
MCS 2007				0.0002(0.003)

Standard Errors in parentheses, Source: ICT indicators are from International Telecommunication Union Website (2008); indexes for Civil Liberties and Political Rights are Freedom House website (2008); Economic Freedom index is from the Heritage Foundation website (2008); Education Index is from UNDP – Human Development Report 2008; Standard and Poor's Global Water Index website (2008); all other variables are from World Development Indicators CD-ROM (World Bank, 2008).

however, this is not statistically significant.

However, House (1999) observed the role of ICTs in enabling greater access to water related issues/information. More so, Baliamoune-Lutz (2003) argued that ICT also foster the development of NGOs and information and Knowledge based communities that are more capable (relative individual citizen) to cause institutional changes. Consequently we expected efficient management of our cross border water resources as our stock of ICT increases in depth and breath. ICT diffusion may also affect the degree of effectiveness of the civil society and structures of the water industry across West African countries. For example, because water consumers have access to indexes and statistics of water coupled with market prices on World Wide Web, they can quickly organize around a problem, mount pressure and initiate a change process. The monopoly, strict control/limited access to knowledge hoisted on the populace by most West African government would become a thing of the past. Competition in the safe drinking water industry would amount to efficient use of resource and civic society watchful eyes through an active online community would act as a deterrent to waste and government excesses. The coefficient of correlation between Fresh water supply, safe Drinking Water is weak and highly significant (Table 1) this may reflect increased integration of these indicators.

DISCUSSION OF EMPIRICAL RESULTS

Equation (1) results from the model exploring the factors that influence WRM performance indicators are represented in Table 2 (Equations 1 to 4). To test the robustness of the model, four equations were estimated. Table 2 displays the statistical results from estimating the model with Fresh Water as the relevant WRMPI variable. Equation 1 uses consumer price inflation, political rights, index of economic freedom, per capita income, human development index, corruption index, secondary school enrolment rate and civil liberties in Equation (2) we excluded consumer price inflation and political rights. In Equation (3) we excluded corruption index and brought in net financial flows while in Equation (4), ICT indicators – Internet Users, broadband subscribers and mobile cell phone subscribers were brought in. Only variable that exhibits high significance will be discussed and estimate of all models is estimated using SPSS (Version 11.00).

In Table 2, Equation (1) displays the estimates using fresh water supply as the WRMP indicators. The empirical results shows these variables are strongly significant policy variables, per capita income, political rights, and liabilities, human development index and corruption index. More so, fresh water supply is assumed to be in the government's exclusive control. The variables that returned as not significant are index of economic freedom and secondary school enrolment rates. Effective management of our water is done by experts and politicians probably. Secondary school enrollment rate, theoretically seen as crucial part, does not really add the needed value statistically. This is so because in most West African Countries you do not need much education to get involve politics. However, finding of a negative effect may suggest there is a link.

Interestingly as expected all ICT indicators reported very significant (Table 2, Equation 4) from the theoretical point view increased broadband subscribers should boost WRMPI. Having a negative effect could suggest that some members of the elite that have laptops and wireless

Table 3. An Economic Assessment of the Impact of ICT on Performance Indicators of Water Resource Management in West Africa Dependent Variable: SDW.

Equations	1	2	3	4
Number of observations	53	53	53	53
Adjusted R^2	0.347	0.355	0.344	0.308
Constant	69.579	68.754	68.433	73.216
PCI	0.0006(0.001)	-0.0006(0.001)	-0.0006(0.001)	0.0004(0.001)
IEF	0.002(0.031)	-0.0002(0.031)	-0.020(0.031)	0.020(0.032)
SER	0.212(0.099)	0.204(0.097)	0.199(0.098)	0.129(0.117)
HDI	0.008(0.055)	-0.084(0.055)	-0.086(0.055)	-0.090(0.058)
CI	4.729(3.107)	4.901(3.076)	5.217(3.159)	4.959(3.438)
CL	-4.088(3.396)	-2.094(1.536)	-2.075(1.549)	-3.616(3.521)
PR	1.687(2.558)			0.768(2.714)
CPI	-0.0002(0.030)	0.007(0.029)	-0.007(0.029)	-0.003(0.032)
NFF			-0.0005(0.001)	0.0001(0.001)
MCS 2002				0.0018(0.002)
MCS 2007				-0.0014(0.000)
BS				-0.046(0.047)
IU				0.0001(0.002)

Standard Errors in parentheses, Source: ICT indicators are from International Telecommunication Union Website (2008); indexes for Civil Liberties and Political Rights are Freedom House website (2008); Economic Freedom index is from the Heritage Foundation website (2008); Education Index is from UNDP – Human Development Report 2008; Standard and Poor's Global Water Index website (2008); all other variables are from World Development Indicators CD-ROM (World Bank, 2008).

web access are yet not actively involved in water issues. If there is an increase in number of subscribers in the future then there could be a point where safe drinking water would be solely private sector controlled. The segment of the industry would be comprised of bottle and sachet water companies, private water distributors, and bore hole drilling firms.

In Table 3, the R-squared is fairly low compared to Fresh Water which is very low. Access to safe drinking water appears to be most influenced by internet Users. In addition, results indicate that factor such as secondary school enrolment rates, corruption index, civil liberties; human development index and political rights are not statistically significant. This is not surprising as corruption in the water sector is negligible. Pricing data and orders placed on the net or otherwise distributed are basically the essential ingredients that is expanding this industry in Africa. Competition is the order of the day in countries such as Ghana and Egypt. Since this is private sector led and statistics seems to solidly support the idea; market oriented variable such as per capita income index of economic freedom, consumer price inflation, net financial flows, political rights, mobile phone subscribers, internet users were strongly significant.

If you compare the relevant variables in Table 3 (private sector) to Table 2 (public sector) you will notice that the difference in policy is statistically relevant. For instance, net financial flows and index of economic freedom were not significant variables in influencing fresh water supply but were highly significant in influencing access to safe drinking water which within the domain of the private sector as against the former assumed to be exclusively controlled by the various West African states. Also, comparing Equations 1 to 4 in Table 3, you notice that equation that has all policy (irrespective of the sector) provides the best results in terms of R-square, 0.481.

The impact of population dynamics on Fresh water supply informed the use of the ratio – FWS/POP. This indicates the tendency of nation states to go war on water issues due to pressures arising from population dynamics. Both equations capture the process and show corruption index the most influential. Others are index of economic freedom, human development index and civil liberties. But human development index has a wrong sign (though statistically significant). It simply shows that improvement in human capital in West African countries does not necessarily translated into improving their water situation. This finding is similar to Broadband Subscribers notwithstanding, human capital and broadband subscribers must have positive roles in the effective management of fresh water supply but may be one possible reason for this anomaly. There could have been serious data measurement error.

In summary, the empirical results provide strong support for the role of ICT indicator as a major determinant of effective water resources management. This is consistent with the conclusion the studies of Van et al. (2003), Koinsky et al. (2001) and Swinford et al. (2007). Similarly all freedom indicators namely civil

Table 4. An Economic assessment of the impact of ICT on performance indicators of water resource management in West Africa Dependent Variable: FWS/POP.

Equations	1	2	3	4
Number of observations	53	53	53	53
Adjusted R^2	0.135	0.153	0.153	0.078
Constant	28.821	35.095	34.002	38.063
PCI	0.006(0.002)	-0.006(0.002)	-0.006(0.002)	0.006(0.002)
IEF	0.03(0.069)	-0.03(0.067)	-0.03(0.067)	0.030(0.070)
SER	-0.662(0.217)	-0.663(0.215)	-0.663(0.215)	-0.711(0.255)
HDI	0.06(0.122)	-0.07(0.119)	-0.07(0.119)	-0.070(0.128)
CI	0.661(6.639)	-0.150(6.776)	-0.150(6.776)	-0.328(7.418)
CL		-0.655(3.366)	-0.655(3.366)	-1.0256(3.615)
PR	0.371(2.583)			
CPI	-0.008(0.064)			
MCS 2002				-0.0008(0.004)
MCS 2007				-0.00009(0.001)
BS				-0.03(0.089)
IU				0.0002(0.004)

Standard Errors in parentheses, Source: ICT indicators are from International Telecommunication Union Website (2008); indexes for Civil Liberties and Political Rights are Freedom House website (2008); Economic Freedom index is from the Heritage Foundation website (2008); Education Index is from UNDP – Human Development Report 2008; Standard and Poor's Global Water Index website (2008); all other variables are from World Development Indicators CD-ROM (World Bank, 2008).

liberties, political rights and index of economic freedom influence the performance of WRM (Table 4).

Impact of selected economic and social development indicators on west water resource management

$$WRMPIi = \alpha + \delta' Z_i + \varepsilon_i \quad (2)$$

Where the vector Z contains economic and social indicators and ε_i is white noise. The only significant variable (though moderate) is fresh water supply followed by internet penetration index that showed p value. Meanwhile Equation (2) shows access to safe drinking water and internet penetration index returns significant (Table 5). In Table 6, Equation (1) report estimates of the impact of selected economic and social indicators as well as WRMPI on income (log transformation of per capita income). ICS, Inter Country scale is a dummy variable for representing UNDP's classification based on HDI as high, medium and low. In our case, 1 stands for countries grouped as medium and 0 for those that were grouped low.

These results indicates that an effective management of cross border and intra border water resource in both sectors of the economy increase in the subsector of cyber and broadband application, would lead to higher per capita income. From our selection the variable that seems to influence income are secondary school enrolment rate, human development index and inter country scale. The is plausible as secondary school enrolment in most West African economies is low. This will directly affect West Africa's Human Development Index which as a result is grossly low.

In theory education is expected to have a positive influence on management of resources. As consumer of sachet and bottle water, for instance, have access to more learning (post primary) it should in turn have a huge impact on politicians who majorly are in charge and monopolize decision making processes. However, the empirical literature presents another picture. In most West African countries school enrolment is quite low. More so, those that enrol do graduate. On the other hand having successful private sector led water firms may not necessarily mean that they are run by secondary school graduates.

In many developing countries, most powerful politicians are ex-military men with little or no formal education. The results in Table 7 seem to support this view. There is no empirical evidence in support of the influence of education on water resource management. Because economic freedom diffusion of ICT and efficient macroeconomic policies improves the changes of managing our water better thereby averting water wars, it is expected to foster economic development in an unprecedented scale as water permeates all facets of the society and economy. This is also supported in Table 8.

Concluding comments

This paper examined the relationship between selected social and economic development, information

Table 5. An Economic Assessment of the Impact of ICT on Performance Indicators of Water Resource Management in West Africa Dependent Variable: SDW/POP.

Equations	1	2
Number of observations	53	53
Adjusted R^2	0.089	0.093
Constant	138.061	35.095
PCI	0.02(0.009)	-0.006(0.002)
IEF	-0.258(0.301)	-0.03(0.067)
SER	1.062(1.085)	-0.663(0.215)
HDI	-0.361(0.540)	-0.07(0.119)
CI	5.404(31.816)	-0.150(6.776)
CL	-18.235(32.584)	-0.655(3.366)
PR	0.08(25.118)	
CPI	-0.04(0.296)	
NFF	0.006(0.010)	
MCS 2002	0.003(0.020)	
MCS 2007	-0.004(0.004)	
BS	-0.036(0.433)	
IU	0.01(0.020)	

Standard Errors in parentheses, Source: ICT indicators are from International Telecommunication Union Website (2008); indexes for Civil Liberties and Political Rights are Freedom House website (2008); Economic Freedom index is from the Heritage Foundation website (2008); Education Index is from UNDP – Human Development Report 2008; Standard and Poor's Global Water Index website (2008); all other variables are from World Development Indicators CD-ROM (World Bank, 2008).

Table 6. An Economic Assessment of the Impact of ICT on Performance Indicators of Water Resource Management in West Africa. Dependent Variable: PCI.

Equations	1	2
Number of observations	53	53
Adjusted R^2	0.374	0.377
Constant	3.038	2.504
IEF	0.008(0.001)	0.008(0.003)
SER	0.031(0.010)	0.027(0.010)
HDI	0.013(0.005)	0.013(0.005)
ICS	1.513(0.889)	1.413(0.900)
IPI	0.037(0.039)	0.031(0.040)
SDW		0.099(0.014)

Standard Errors in parentheses, Source: ICT indicators are from International Telecommunication Union Website (2008); indexes for Civil Liberties and Political Rights are Freedom House website (2008); Economic Freedom index is from the Heritage Foundation website (2008); Education Index is from UNDP – Human Development Report 2008; Standard and Poor's Global Water Index website (2008); all other variables are from World Development Indicators CD-ROM (World Bank, 2008).

communication technology and water resource management performance indicators, ICT are a major determinant of water resource management performance indicator. It influences civil societies providing a veritable platform for actively sharing information on an international scale and engaging government agents to further entrench the culture of excellence and corporate governance. These platforms enable West African economies imbibe international best practices that evolve over time thereby forcing respective governments to be accountable and transparent which are hallmarks of the ongoing anti water war campaigns. Secondly, there is a strong influence of macroeconomic policies on the sector. Third, freedom improves the water resource management. Fourthly, empirical results support the notion that effective management of our water resources

Table 7. An Economic Assessment of the Impact of ICT on Performance Indicators of Water Resource Management in Africa. Dependent Variable: SER.

Equations	1	2
Number of observations	53	53
Adjusted R^2	0.468	0.093
Constant	35.422	35.095
IEF	0.048(0.045)	-0.03(0.067)
SER	1.062(1.085)	-0.663(0.215)
HDI	-0.136(0.072)	-0.07(0.119)
ICS	4.419(13.410)	-0.150(6.776)
IPI	2.279(0.486)	
FWS KM^3/yr	-0.019(0.015)	

Standard Errors in parentheses, Source: ICT indicators are from International Telecommunication Union Website (2008); indexes for Civil Liberties and Political Rights are Freedom House website (2008); Economic Freedom index is from the Heritage Foundation website (2008); Education Index is from UNDP – Human Development Report 2008; Standard and Poor's Global Water Index website (2008); all other variables are from World Development Indicators CD-ROM (World Bank, 2008).

Table 8. An Economic Assessment of the Impact of ICT on Performance Indicators of Water Resource Management in West Africa Dependent Variable: CL.

Equations	1	2
Number of observations	53	53
Adjusted R^2	0.119	0.033
Constant	7.385	5.066
IEF	-0.012(0.003)	-0.0009(0.003)
HDI	-0.007(0.005)	-0.006(0.005)
ICS	1.247(0.894)	0.851(0.033)
IPI	-0.034(0.035)	-0.655(3.366)
SDW	0.034(0.013)	
FWS KM^3/yr		0.0013(0.001)

Standard Errors in parentheses, Source: ICT indicators are from International Telecommunication Union Website (2008); indexes for Civil Liberties and Political Rights are Freedom House website (2008); Economic Freedom index is from the Heritage Foundation website (2008); Education Index is from UNDP – Human Development Report 2008; Standard and Poor's Global Water Index website (2008); all other variables are from World Development Indicators CD-ROM (World Bank, 2008).

will help to develop West Africa's economy. Also, enhance political rights and civil liberties. It must be pointed out here that in West African countries, based on statistical analysis, education is not associated with effective water resources management.

The present finding seems to offer some new strategies embedded in an ICT – oriented culture for managing our nation's water resources. It would also compliment concerted efforts to boost irrigation farming in West Africa as Valipour (2014b) observed that the respective government should encourage irrigation farming. There is ample evidence that managing our water resources effectively can provide an additional source of economic growth. On the other hand, this paper provides crucial insights about those ICT, economic and social development variables that are important parts of WRMPI.

Conflict of Interest

The authors have not declared any conflict of interest.

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Numerical simulation of groundwater recharge from an injection well

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This paper presents the numerical simulation of groundwater recharge from a point source, that is, injection well using Explicit Finite Difference Model (FDFLOW) and Galerkin Finite Element Model (FEFLOW). The proposed model aims at simulation of groundwater flow in two-dimensional, transient, unconfined aquifer for a chosen synthetic Test Case. These models are validated with reported analytical solutions for a test run period of 210 days. It is found that the FEFLOW model performed better than FDFLOW model in terms of conservation of mass and oscillations in numerical solutions. For simulation of recharge from an injection well test run period of 1500 days is considered. The accretion in groundwater volume from an injection well is analyzed. Further the effect of injection rate of a well and aquifer parameter is analyzed on model results. It is found that both the model solutions are highly sensitive to injection rate and moderately sensitive to transmissivity whereas the specific yield has negligible effect on numerical solutions.

Key words: Explicit Finite Difference Model (FDFLOW), Finite Element Model (FEFLOW), model validation, mass balance, courant number, sensitivity of models to recharge rate, transmissivity and specific yield.

INTRODUCTION

Due to global warming it has become the need of the hour that ever depleting groundwater resources are to be continuously replenished using modern artificial recharging techniques. This has drawn the attention of researchers worldwide to device and use variants of numerical models for simulation of the hydrologic process of groundwater recharge.

It is found that Explicit Finite Difference Model (FDFLOW) and Finite Element Model (FEFLOW) models provide meaningful simulations of recharge from injection well to aquifers than available physical and electric-analog models; moreover, these models provide ease in simulating complex aquifer geometry and varying aquifer parameters. Because these are quite so, numerical models of groundwater flow are properly conceptualized version of a complex aquifer system which approximates the flow phenomenon.

The approximations in the numerical models are effected through the set of assumptions pertaining to the geometry of the domain, ways the heterogeneities are smoothed out, the nature of the porous medium, properties of the fluid and the type of the flow regime.

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The complex aquifer system is treated as a continuum, which implies that the fluid and solid matrix variables are continuously defined at every point in the aquifer domain. The continuum is viewed as a network of several representative elementary volumes, each representing a portion of the entire volume of an aquifer with average fluid and solid properties taken over it and assigned to the nodes of superimposed grid used for the spatial discretization of the domain. Anderson and Woessner (1992) discussed that numerical models also help in synthesizing field information and handling the large amount of input data in regional scale problems.

Wang and Anderson (1982) discussed that numerical models are applied either in an interpretive sense to gain insight into controlling the aquifer parameters in a site-specific setting or in generic sense to formulate regional regulatory guidelines and act as screening tools to identify regions suitable for artificial recharge by various methods.

Tseng and Ragan (1973) analyzed the dynamic response of the two-dimensional unconfined aquifers subject to localized recharge in both fully and partially penetrated aquifer systems by finite difference method. This method treats the nonlinear free surface boundary as an initial condition and the overall flow region has been solved as boundary value problem. The variations of free surface profiles with respect to time are also analyzed.

Sucharit and Parot (2001) conducted groundwater movement study in north part of lower central plain of Thailand by MODFLOW model. Both the steady and transient state models were calibrated with the observed data. The model also provided flow water balance. From sensitivity analysis of model results, it was found that the groundwater flow simulations are more sensitive to hydraulic conductivity.

Thomson et al. (1984) presented a Galerkin finite element model using Picard and Newton-Raphson algorithms designed for solution of non-linear groundwater flow equation. The model uses both triangular and rectangular finite elements for aquifer discretization. The influence area coefficient technique is used instead of conventional numerical integration scheme to obtain element matrices. It is found that this new technique is successful in reduction of computational cost.

Fagherazzi et al. (2004) developed the discontinuous Galerkin method which uses a finite-element discretization of the groundwater flow domain. Their model used an interpolation function of an arbitrary order for each element of the domain. The independent choice of an interpolation function in each element permits discontinuities in transmissivity in the flow domain. This formulation is shown to be of high order accuracy and particularly suitable for accurately calculating the flow field in porous media.

Chen and Chau (2006) have discussed the use of knowledge-based system technology along with the heuristic knowledge of model for manipulation of models for hydrologic system. Further they employed expert system shell in prototype knowledge-based system for modeling hydrologic processes.

Muttil and Chau (2006) applied machine learning (ML) techniques and genetic programming (GP) for modeling and prediction of ecological parameters in flow system. It is found that these techniques are proved to be useful for prediction of long term trends in flow system.

Chau (2007) discussed the integration of numerical simulation of flow with ontology based knowledge management (KM), artificial intelligence technology with the conventional hydraulic algorithmic models in order to assist novice application users in selection and manipulation of various mathematical tools and a Java/XML-based scheme for automatically generating knowledge search components.

The objectives of the present study are: development of FDFLOW and FEFLOW models for simulation of recharge from an injection well; validation of developed FDFLOW and FEFLOW models; evaluation of the performance of the models based on mass balance and stability criteria; analysis of the sensitivity of the model solutions to aquifer parameters viz. transmissivity and specific yield and injection rate.

MODEL DEVELOPMENT

Groundwater flow equation

The governing equation of two-dimensional, horizontal, and transient groundwater flow in homogeneous, isotropic and unconfined aquifer is given by Illangasekare and Doll (1989),

$$S_y \frac{\partial h}{\partial t} = T_{xx}\frac{\partial^2 h}{\partial x^2} + T_{yy}\frac{\partial^2 h}{\partial y^2} + \sum_{i=1}^{n_w} Q_i\,\delta(x_o - x_i, y_o - y_i) \qquad (1)$$

where S_y is the specific yield, [dimensionless]; h is the hydraulic head averaged over vertical, [L]; t is the time, [T]; T_{xx} and T_{yy} are components of the transmissivity tensor, [L^2/T] which are approximated as $T_{xx} \approx K_{xx}\,h$ and $T_{yy} \approx K_{yy}\,h$, provided the change in the head in unconfined aquifer is negligible as compared to its saturated thickness; K_{xx} and K_{yy} are components of the hydraulic conductivity tensor, [L/T]; x and y are spatial coordinates, [L]; Q_i is the injection rate at i th injection well, [L^3/T]; n_w is the number of injection wells in the domain; $\delta(x_o - x_i, y_o - y_i)$ is the Dirac delta function; x_o and y_o are the Cartesian coordinates of the origin , [L]; x_i and y_i are the coordinates of i th injection well, [L]. Equation (1) is subject to the following initial condition which is given as:

$$h(x,y,0) = h_0 \qquad (x,y) \in \Omega \qquad (2)$$

Where h_0 is the initial head over the entire flow domain, [L] and Ω is the flow domain, [L^2]. Equation (1) is subject to the Dirichlet type of boundary condition which is given as:

$$h(x, y, t) = h_1 \qquad (x, y) \in \Gamma_1; \quad t \geq 0 \tag{3}$$

Where h_1 is the prescribed head over aquifer domain boundary Γ_1, [L].

The Neumann boundary condition with zero groundwater flux can be given as:

$$\left[\{q_b(x, y, t)\} - [T]\nabla h(x, y, t)\right]' . \{n\} = 0 \qquad (x, y) \in \Gamma_2; \; t \geq 0 \tag{4}$$

Where q_b is the specified groundwater flux across boundary Γ_2, [L/T]; $[T]\nabla h$ is the groundwater flux across the boundary Γ_2, [L/T] and n is normal unit vector in outward direction.

FDFLOW model

The explicit finite difference method is employed in FDFLOW model to solve Equation (1). In this model the unknown nodal head at next time level is explicitly computed from the four neighboring nodes with known heads at the previous time level. The explicit finite difference scheme is adopted because, it is computationally efficient than the alternating direction implicit finite difference scheme, but it has the restriction of the size of time step used in simulation. However, the stability of the solutions can be ensured by constraining the length of a time step. In this model the entire aquifer domain is discretized into rectangular computational cells by superimposing the mesh centered finite difference grid over the domain.

The computational cells are formed around the intersection points of grid column and row lines which are referred to as a node. Thus each node with grid column index i and grid row index j represents a computational cell. The size of each rectangular computational cell is Δx and Δy in x- and y- directions respectively.

In FDFLOW model, the spatial derivatives and temporal derivative in Equation (1) are approximated by central finite difference and forward difference schemes respectively which will result into the following equation

$$\frac{S_{y_{i,j}}(h_{i,j}^{t+\Delta t} - h_{i,j}^{t})}{\Delta t} = \frac{(T_{xx_{i,j}}(h_{i+1,j}^{t} - 2h_{i,j}^{t} + h_{i-1,j}^{t}))}{\Delta x^2} + \frac{(T_{yy_{i,j}}(h_{i,j+1}^{t} - 2h_{i,j}^{t} + h_{i-1,j}^{t}))}{\Delta y^2} + \frac{Q_{i,j}}{\Delta x \, \Delta y} + q_{i,j} \tag{5}$$

Equation (5) can be expressed in matrix form as:

$$\begin{Bmatrix} h_1^{t+\Delta t} \\ h_2^{t+\Delta t} \\ . \\ . \\ h_N^{t+\Delta t} \end{Bmatrix} = \begin{bmatrix} \left(\frac{T_{xx_1}\,\Delta t}{S_{y_1}\,\Delta x^2}\right) & 0 & 0 & 0 \\ 0 & \left(\frac{T_{xx_2}\,\Delta t}{S_{y_2}\,\Delta x^2}\right) & 0 & 0 \\ 0 & 0 & - & 0 \\ 0 & 0 & 0 & \left(\frac{T_{xx_N}\,\Delta t}{S_{y_N}\,\Delta x^2}\right) \end{bmatrix} + \begin{bmatrix} \left(\frac{T_{yy_1}\,\Delta t}{S_{y_1}\,\Delta y^2}\right) & 0 & 0 & 0 \\ 0 & \left(\frac{T_{yy_2}\,\Delta t}{S_{y_2}\,\Delta y^2}\right) & 0 & 0 \\ 0 & 0 & - & 0 \\ 0 & 0 & 0 & \left(\frac{T_{yy_N}\,\Delta t}{S_{y_N}\,\Delta y^2}\right) \end{bmatrix} \begin{Bmatrix} h_1^{t} \\ h_2^{t} \\ . \\ . \\ h_N^{t} \end{Bmatrix} \tag{6}$$

Thus the unknown nodal head vector in Equation (6) is solved using the direct matrix inversion technique available in MATLAB environment.

FEFLOW model

This model employs the Galerkin finite element technique for computing the head distribution in aquifer. In this method the trial solution of the head is substituted into Equation (1) which results into the residual. By using the weighting functions as the shape functions, the weighted residual is integrated and forced to zero to yield the system of linear equations. The set of the linear equations is solved to get the nodal head distribution. The groundwater flow domain is discretized into finite number of nodes using a triangular finite element mesh.

Each node of the domain is identified by an index L and the finite element by an index e. The three nodes of a finite element are labeled as i, j and k in either clockwise or anticlockwise manner. The time domain is discretized into finite number of discrete time steps. The size of each time step is Δt. The trial solution of the groundwater head to be used in finite element formulation is given as:

$$\hat{h}(x, y, t) = \sum_{L=1}^{N} h_L(t)\, N_L(x, y) \tag{7}$$

Where $\hat{h}$ is the trial solution of groundwater head, [L]; N is the total number of nodes in the flow domain; h_L is the nodal groundwater head at any time t, [L]; N_L is the linear shape function at any point (x, y) in the aquifer domain. The shape function is defined piecewise but in continuous manner over entire flow domain which ranges from 0 to 1. The trial solution is substituted for unknown nodal head h in Equation (1) which results into the residual of groundwater head which is expressed as:

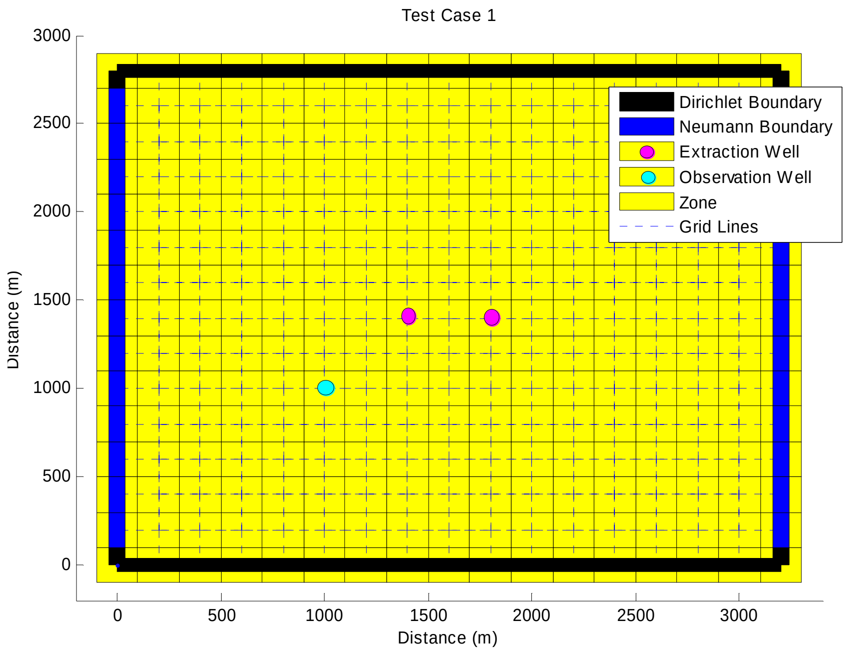

Figure 1. Schematic of aquifer modeled in chosen synthetic Test Case 1 for the validation of FDFLOW and FEFLOW models.

$$\varepsilon^h(x,y,t)=T_{xx}\frac{\partial^2 \hat{h}}{\partial x^2}+T_{yy}\frac{\partial^2 \hat{h}}{\partial y^2}+\sum_{i=1}^{n_w} Q_i\delta(x_o-x_i,y_o-y_i)-S_y\frac{\partial \hat{h}}{\partial t} \quad (8)$$

Where ε^h is the residual of groundwater head at any point (x, y) and at time t; $[L]$. The residual of the head is weighted and integrated over entire flow domain to obtain the nodal head distribution. The integral of the weighted head residual is forced to zero to yield the system of algebraic equations and the same is given as:

$$\iint_\Omega \left(T_{xx}\frac{\partial^2 \hat{h}}{\partial x^2}+T_{yy}\frac{\partial^2 \hat{h}}{\partial y^2}+\sum_{i=1}^{n_w} Q_i\delta(x_o-x_i,y_o-y_i)-S_y\frac{\partial \hat{h}}{\partial t}\right) W_L\, dx\, dy=0 \quad (9)$$

Where W_L is the weighting function at a node L. Applying the numerical integration for the various terms of Equation (7) the following system of linear equations is obtained and the same can be written as:

$$\left([\boldsymbol{G}]+\frac{1}{\Delta t}[\boldsymbol{P}]\right)\{h_{i,j}^{t+\Delta t}\}=\left(\frac{1}{\Delta t}[\boldsymbol{P}]\right)\{h_{i,j}^{t}\}+\{\boldsymbol{B}\}+\{\boldsymbol{f}\} \quad (10)$$

Where $[\boldsymbol{G}]$ is the global conductance matrix, $[\boldsymbol{P}]$ is the global storage matrix, $\{\boldsymbol{B}\}$ is the global load vector and $\{\boldsymbol{f}\}$ is the global boundary flux vector. From the known head distribution at previous time level the unknown head distribution at the next time level is obtained by recursively solving the set of algebraic equations given in Equation (10).

RESULTS AND DISCUSSION

Validation of numerical models

The chosen synthetic Test Case 1 is aimed at validating the FDFLOW and FEFLOW models. The validation of groundwater flow models is accomplished by comparing model simulations with the reported analytical solutions Illangasekare and Doll (1989). For synthetic Test Case 1 a rectangular, homogeneous, and isotropic unconfined aquifer is chosen as shown in Figure 1. The rectangular aquifer is selected mainly to satisfy the shape constraints imposed for the analytical solution. The aquifer system is

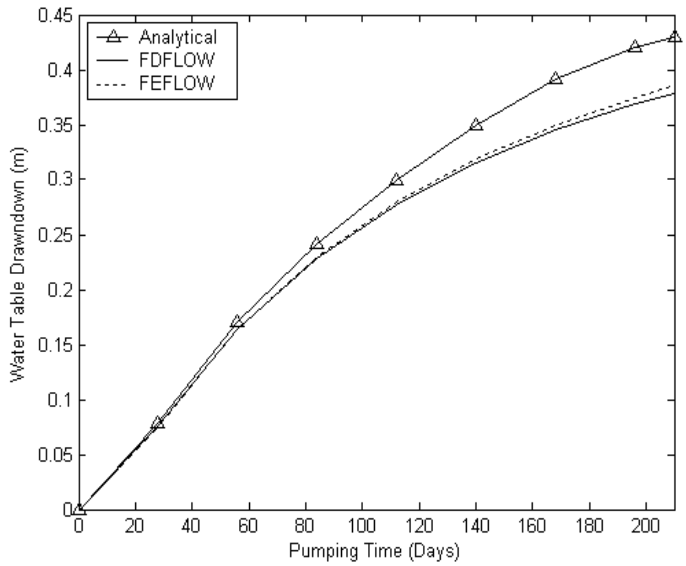

Figure 2. Validation of FDFLOW and FEFLOW models for synthetic Test Case 1.

3,200 m long and 2,800 m wide. The head at the top and bottom sides of the aquifer boundary is considered to have constant value of 100 m throughout the simulation, and left and right sides of the aquifer boundary is considered to have zero groundwater flux. Two pumping wells are placed at a location of (1400 m, 1400 m) and (1800 m, 1400 m) from the origin, as shown in Figure 1. Initially the groundwater head is assumed static with a value of 100 m at all nodes in the aquifer domain. The water table drawdown caused by pumping are observed at an observation well situated at a location of (1000 m, 1000 m) from the origin.

The aquifer parameters used in the simulation include aquifer thickness (b =30 m), constant pumping rates for the two pumping wells (Q_{p1} & Q_{p2} = 1142.85 and 1428.57 m^3/d), effective porosity (θ =0.30), aquifer transmissivty (T =885.71 m^2/d) and specific yield (S_y =0.15) respectively. For FDFLOW model, the aquifer is discretized using mesh centered finite difference grid which results into 255 computational cells with uniform nodal spacing of 200 m in both x- and y- directions. For FEFLOW model, the aquifer is discretized using the triangular finite element mesh with 448 elements. The size of the square finite difference cell and isosceles triangular element is 200 m. Total nodes with Dirichlet boundary condition and Neumann boundary conditions are 32 and 28, respectively.

The water table drawdown values at an observation well due to the pumping by pair of wells for 210 days are computed by FDFLOW and FEFLOW models. The time-drawdown curves obtained by FDFLOW and FEFLOW models and reported analytical solution Illangasekare and Doll (1989) are compared as shown in Figure 2. The drawdown values are computed as 0.38 and 0.39 m by FDFLOW and FEFLOW models respectively which are quite comparable with the reported drawdown of 0.42 m by analytical solution implying the validity of the developed flow models.

The mass balance error analysis for the flow models used in numerical experiments for Test Case 1 showed that both the FDFLOW and FEFLOW conserves the mass satisfactorily and the average mass balance error in both the models is well within the limit i.e. up to 0.69%.The FDFLOW and FEFLOW model solutions are found to be stable for the Courant number of 0.14 for the chosen time step of 1 day.

Simulation of recharge from injection well

This Test Case 2 (Illangasekare and Doll, 1989) is aimed at simulating the groundwater flow behavior under the condition of recharge from injection well. The aquifer and flow parameters, initial and boundary conditions and spatial discretization used in this Test Case are same as that of synthetic Test Case 1 except that of different specific yield of 0.10 and test period of 1500 days (Figure 3). An injection well situated at the location of (2200 m, 1800 m) recharges the aquifer at the constant rate of 8214.28 m^3/d.

The rise in water table caused by recharge to the aquifer from injection well is observed at an observation well situated at a location of (1800 m, 1000 m). The head distribution obtained by both the models is compared. The sensitivity of time-accretion curve obtained by

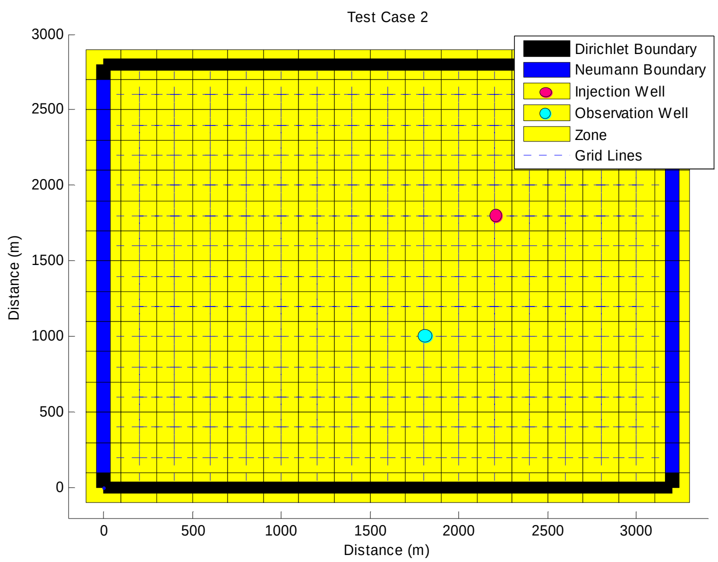

Figure 3. Schematic of aquifer modeled in synthetic Test Case 2 for the simulation of two-dimensional transient groundwater flow in unconfined aquifer under the recharge from an injection well.

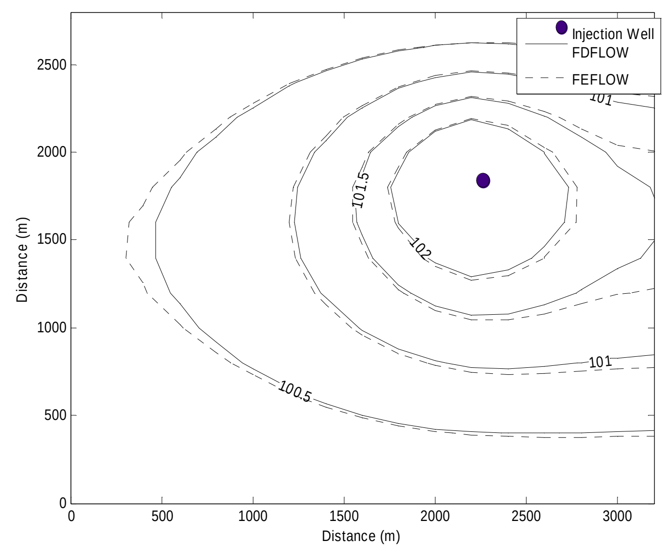

Figure 4. Comparison of groundwater head distribution by FDFLOW and FEFLOW models under the injection well conditions for Test Case.

FDFLOW and FEFLOW models to the variation in transmissivity, specific yield and injection rate have also been studied.

Comparison of head distribution by FDFLOW and FEFLOW models under the recharge from an injection well

The comparison of the groundwater head distribution simulated by FDFLOW and FEFLOW model is shown in the Figure 4. It is found from the results that the maximum rise in water table is noted at the node situated at location (1800 m, 2200 m), which is in close proximity of the injection point is 105.30 and 105.36 m, respectively by FDFLOW and FEFLOW model due to recharge of water from an injection well. The contour of head value of 100.5 m obtained by FEFLOW model has experienced some numerical dispersion due to the effect of zero groundwater flux boundary. The deviation of

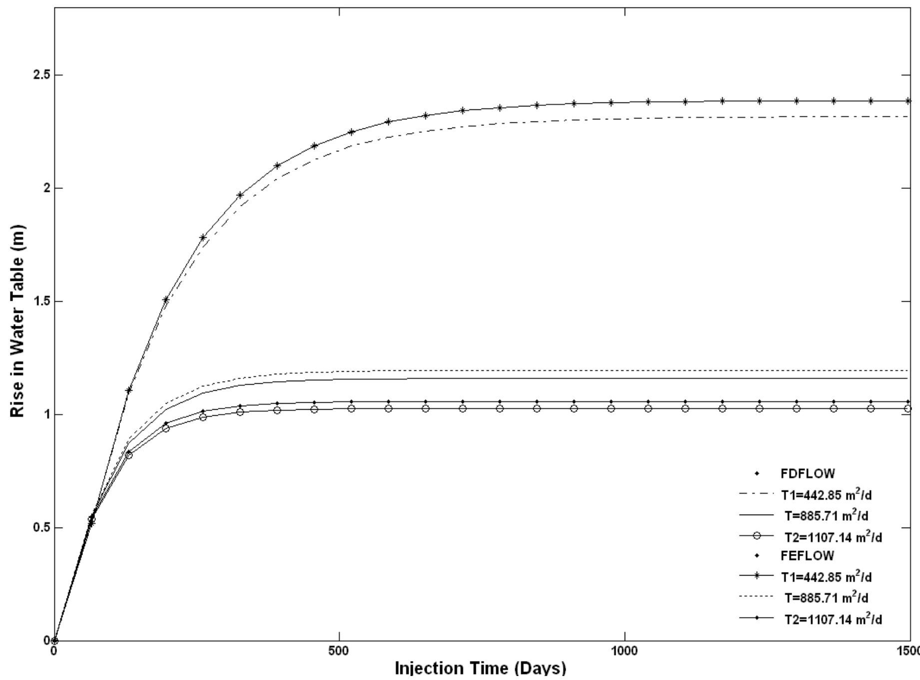

Figure 5. Effect of transmissivity on the rise in water table for synthetic Test Case 2.

FEFLOW computed solutions from analytical solutions in the later stages of simulation may be attributed to lower order interpolation function used in the FEFLOW model.

Effect of transmissivity on rise in water table

Figure 5 shows the plot of rise in water table against the injection time for different values of the transmissivity. The transmissivity values are varied over the range of 442.85 to 1107.14 m^2/d which is -50 to 25% of the base value of the transmissivity that is, 885.71 m^2/d. The increase in transmissivity by 25% results into 11.48% drop in water table rise whereas for the same period of pumping the decrease in transmissivity by 50% causes rise in water table by 100%.

It is seen from the results that the water table rise curves simulated by FEFLOW at the different values of transmissivity lie slightly above those simulated by FDFLOW model. These model solutions are moderately sensitive to the transmissivity of the aquifer as the transmissivity vector is approximated as the product of conductivity vector and saturated thickness and there are not spatial variation of hydraulic conductivity field.

Effect of specific yield on rise in water table

Figure 6 shows the curves of water table rise versus injection time for the different values of the specific yield. The magnitude of the specific yield is varied from 0.09 to 0.30 which is -25 to 200% of its base value which is 0.10. The results showed that the water table is continuously rising with the increase in injection time and after 400 days of injection it starts stabilizing and approaches to the constant value. The variation of the specific yield has lesser impact over the rise in water table for the chosen range of variation in the specific yield. The effect of the specific yield is found to be negligible over the numerical solutions because of constant and less magnitude of specific yield.

Effect of Injection rate on rise in water table

Figure 7 shows the influence of variation in injection rate of the well on the water table rise. The injection rate is varied from -50 to 50% of its base value which is 8214.28 m^3/d. The change in water table rise computed by FDFLOW model is observed to be -50% and +60% for the corresponding variation of injection rate and in case of FEFLOW simulation the change in water table has almost been same for the corresponding range of variation in injection rate because of an appropriate interpolation function used in finite element integration in FEFLOW model in the initial stages of simulation. But as the injection rate increases after 263 days the water table rise curve shifts leftward indicating the stabilization of head buildup at early stage of FDFLOW and FEFLOW solutions are more sensitive to injection rate because approximations in numerical formulations are not able to accurately simulate point source conditions.

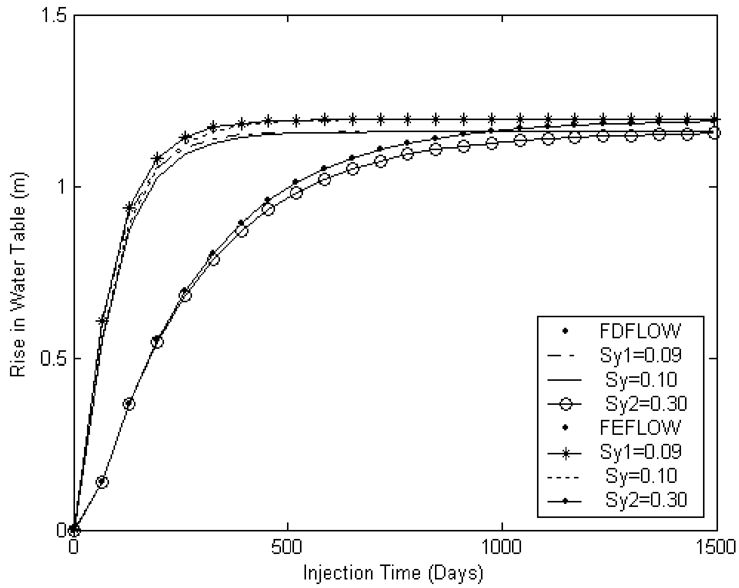

Figure 6. Effect of specific yield on the rise in water table for Test Case 2.

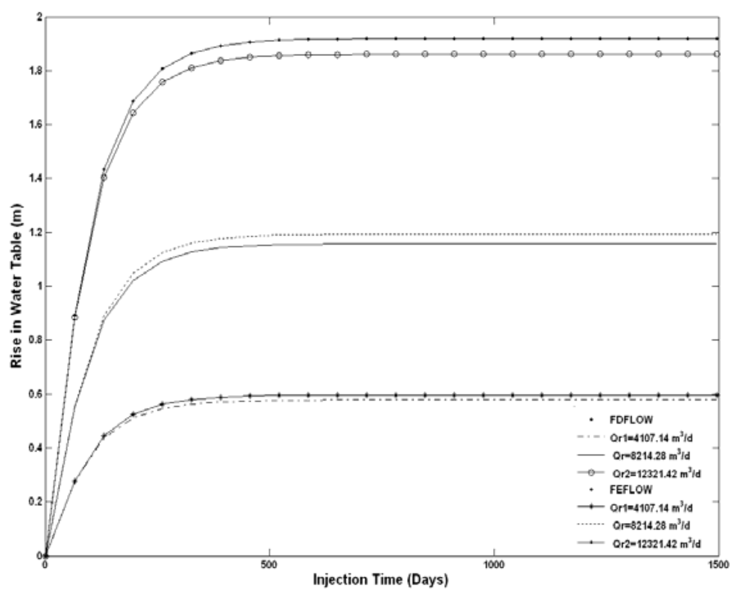

Figure 7. Effect of injection rate on the rise in water table for synthetic Test Case 2.

Conclusions

The following are the conclusions of the present study:

1). Validation of FDFLOW and FEFLOW model for Test Case 1 shows that there is a close agreement between computed and analytical solutions in the initial stages of the pumping, however, after 210 days of pumping the difference between drawdown obtained by FDFLOW and FEFLOW model and analytical solution are 10 and 7% respectively. Thus FEFLOW model has performed better than FDFLOW model.

2). The mass balance error analysis for the flow models used in numerical experiments for Test Case 1 showed that both the FDFLOW and FEFLOW conserves the mass satisfactorily and the average mass balance error

in both the models is well within the limit i.e. up to 0.69%.
3). For Test Case 1, the FDFLOW and FEFLOW model solutions are found to be stable for the Courant number 0.14 for the chosen time step of 1 day.
4). FEFLOW model simulates recharge conditions more accurately than FDFLOW model as evidenced by less numerical oscillations in FEFLOW model solutions.
5). FDFLOW and FEFLOW solutions are more sensitive to injection rate and moderately sensitive to the transmissivity of the aquifer and there is negligible effect of specific yield on model solutions.

The following are the limitations of the study:

1). For larger time step size, FDFLOW model solutions are highly oscillatory.
2). In FEFLOW model, use of linear interpolation function poorly simulates point source conditions.
The present work can be continued further as follows: Long time prediction of the hydraulic head can be made by conducting time series prediction of rainfall and irrigation return flow. Further large time steps can be accommodated in models to make these suitable for coupling with optimization models.

Conflict of Interest

The author have not declared any conflict of interest.

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