A Review of Groundwater and Surface Water Interaction Using Integrated Methods

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Abstract

Water resource management without considering the groundwater and surface water interactions cannot lead to reliable results, especially in the management of rivers and reservoir dams. Application of numerical models is a cost-efficient approach in simulating the water resources issues. In recent years, the number of researches increases significantly in this field. Although there are numerous review articles, which assess and classify the numerical studies in the field of groundwater or surface water management, the lack of information about integrated methods for groundwater and surface water interactions is apparent. This study tends to compare the different methods which are used in groundwater and surface water interaction studies and conclude the advantages and shortcomings of such methods.

Keywords: Groundwater-surface water interaction, Integrated modeling, Water resource management.

1. INTRODUCTION

Groundwater and surface water are two vital parts in the hydrological cycle. Researchers tended to consider them as the separate parts because of complication of simulating their interactions and the noticeable difference in their governing equations. On the other hand, despite the regarded issues, these two parts have a dynamic permanent interaction. Considering an integrated approach, groundwater and surface water interaction occurs in two different ways: groundwater recharge surface water or surface water infiltrates in the soil that leads to groundwater recharge [1]. It should be noticed that both the quality and quantity of each part have a significant effect on the other one.

Nowadays, as we face drought and flood in the vast area of the world, recharging of groundwater resources considering its interaction with surface water plays an important role in water resource management. In recent decades, different approaches have been adopted in simulating groundwater and surface water interactions. One of the first attempts in these studies took place in the 70s, as the concerns about acid rain's environmental impacts increased significantly [1]. Subsequent studies focused on groundwater and surface water interaction in coastlines and marshes because of their massive changes due to human activities [2]. In recent years most of the studies have been conducted to optimize water resource management in river and groundwater interactions. These tendencies towards such studies is a result of three main reasons: 1. Importance of rivers and groundwater resources and their interaction as a significant accessible freshwater resource. 2. Changing in river regime as a result of human activities, especially dams constructions 3. Noticeable increase in river pollution due to human activities, which could lead to groundwater pollution [3].

As groundwater and surface water interactions have different impacts on different aspects of our environment, which is raised various concerns, categorize the previous study is necessary. All of the previous studies, based on their approach, can be categorized as biological, physiochemical, and hydrodynamics [4]. Moreover, in the hydrodynamic approach, the previous study could be categorized based on their surface water hydrodynamic conditions. For instance, coastlines are affected by the tide, which has a great influence on the flow pattern in groundwater and surface water interaction. However, rivers mostly are influenced by their bed characteristics (e.g., permeability and porosity) [5].

Despite the modest increase in computational costs, the importance of using an integrated method in many conditions is not negligible. One of the efficient ways of studying groundwater and surface water interactions is to apply numerical methods to these studies. Previous researches indicate that numerical methods are entirely able to take groundwater and surface water interactions into account [6].

In Iran, with regards to the annual decrease in water table level and water crisis, implement the accurate measures for effective water management are needed more than before. In recent years with enhancing the capability of computers, numerical models turn into a reliable and effective method to study groundwater and surface water interactions. Although there are numerous review articles, which assess and classify the numerical studies in the field of groundwater or surface water management, the lack of information about integrated methods for groundwater and surface water interactions is apparent. Furthermore, use of the integrated methods in different situations and with different scales and existence of various models for simulating groundwater and surface water interactions, increase the importance of categorizing available models to conclude the advantages and shortcomings of such methods. Overall, this study tends to introduce and assess available models and categorize them based on the effect of scale and other conditions, which are involved in the issues.

2. GROUNDWATER SURFACE WATER INTERACTION FIELD SURVEY

Determination of the river interaction with its adjacent aquifer usually needs the hydraulic head in an observation well (hx), the hydraulic head of the river (hr), and the apex elevation of the river bed (hb) [7]. The mentioned parameters are illustrated in Figure.1

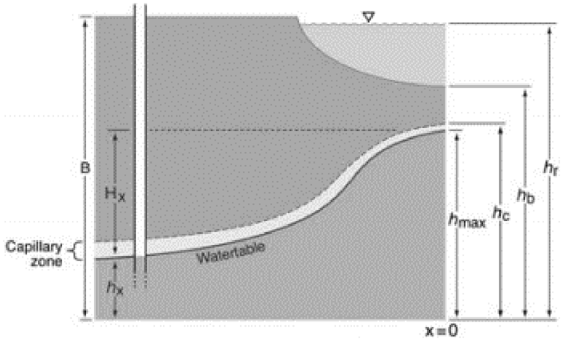

Figure 1. Necessary parameters for determination of river-aquifer interaction [7]

The first step for determination of river-aquifer interaction is comparison piezometric head in river and observation well. As a result, If the river's hydraulic head was above the well's hydraulic head, the river gain water from the aquifer, and if it was lower than the well the aquifer gain water. However, the situation is not always that simple. If there were a confined layer under the river bed, determination of the river-aquifer interaction would not be possible just with the measuring of the hydraulic head in the observation well. In this situation, hc and hmax, which is demonstrated in Figure.1, should be determined. Determination of these two parameters requires the discharge in observation well (qmax). By determining the rate of discharge and using Terzaghi equation hc and hmax will be achieved. Furthermore, the determination of these two parameters would be simpler by using two observation well [7]. After specifying the value of hc and hamx, the following procedure, that is shown in figure.2, should be used to determine river-aquifer interactions. It should be note that all the calculations are made based on hydrostatic assumption

In general, surveying river and aquifer interaction, based on observation data, do not lead to reliable results. Because there is a dynamic interaction between river and aquifer that varies in every single location. In other words, the data set of river-aquifer interaction should be a set of extended data, which determine the amount and orientation of swapped water at different times and places [8]. Numerical methods markedly provide such abilities in their results.

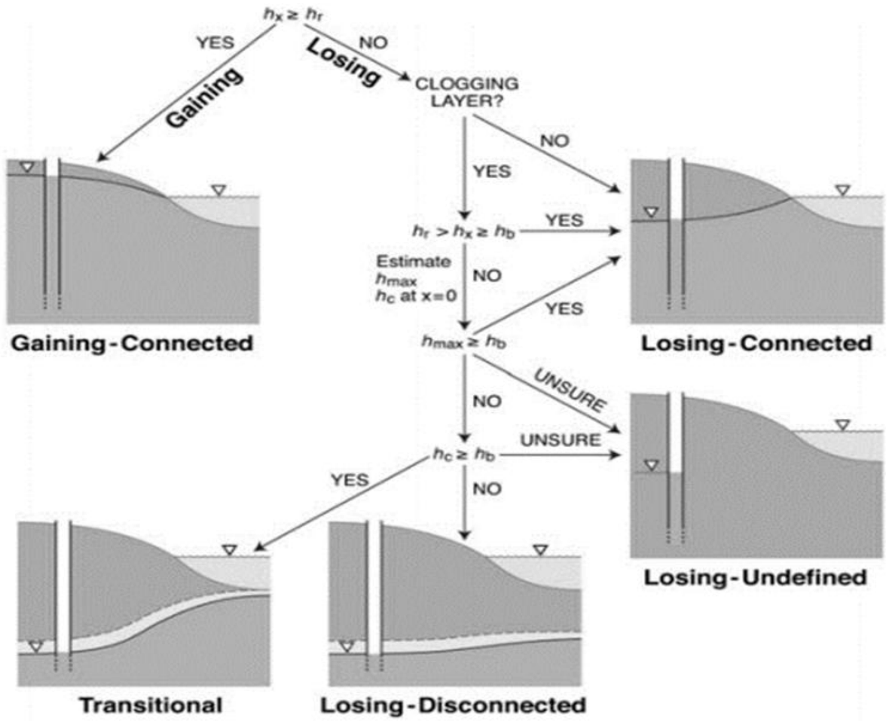

Figure 2. River-aquifer interaction algorithm [7]

3. WATER BUDGETS

Water budget anticipation seems inaccurate without consideration of groundwater surface water interaction [9]. In this case, Groundwater-Surface Water Interface (GWSWI) is the area in which the transition of water takes place [10]. Calculation of water budget considering groundwater surface water interaction is possible with Eq.1:

$$q_{lat} = Q_{dawn} - Q_{up} \tag{1}$$

Where Qdawn is the downstream hydrograph and Qup is the upstream hydrograph.

IWAN is one of the numerical models which can calculate the water budget. This model considering the vertical interaction of groundwater and surface water, also the lateral supply of groundwater in the modeling process. The result is to obtain exchange rates across the river at different times and locations [11]. Figure 3 illustrates the function of the model in the groundwater zone, unsaturated zone, and surface runoff.

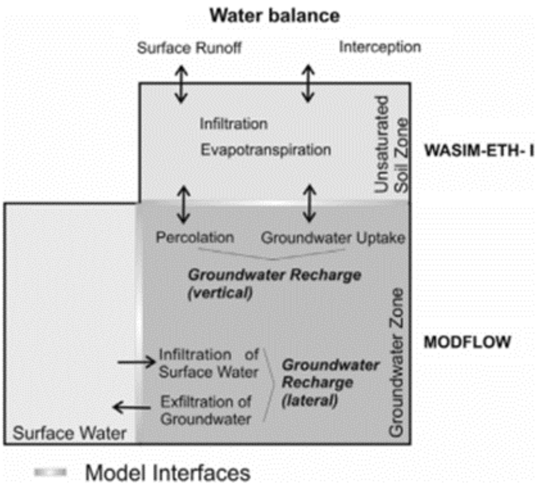

Figure 3. The conceptual function of IWAN model

In this model, the dynamic process in the unsaturated zone and groundwater zone is modeled with the WASIM-ETH-I and MODFLOW, respectively. Surface runoff is not simulated directly in this model. In fact, this model is just simulating the vertical penetration of surface runoff into the unsaturated zone. The exchange rate between groundwater and surface water is being calculated using Eq.2:

$$q = C_{RIV}.\Delta h \tag{2}$$

Where CRIV is leak factor and Δh is the hydraulic gradient, also CRIV could be calculated using Eq.3:

$$C_{RIV} = K_{RIV}.L.\frac{W_{RIV}}{M_{RIV}} \tag{3}$$

Where KRIV is hydraulic conductivity tensor of the river bed, L is river length, WRIV is effective width of the river, and MRIV is the thickness of hyporheic region. Figure4 demonstrates the procedure of exchange flow in WASIM-ETH-I model in the unsaturated zone and recharge and discharge in the MODFLOW model in a real condition.

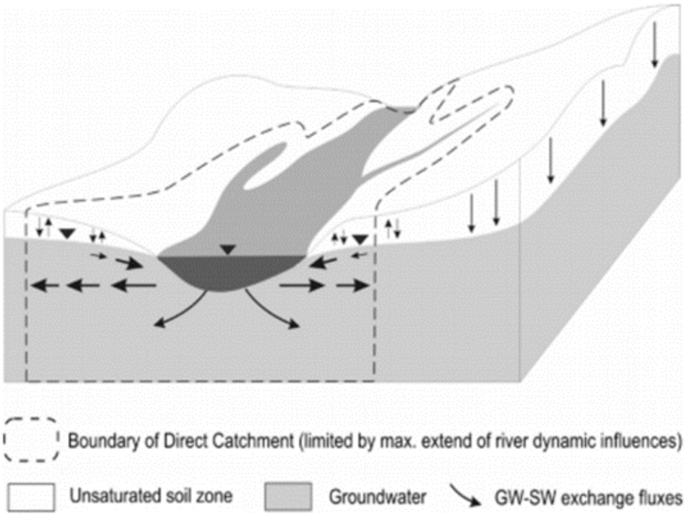

Figure 4. Control range of IWAM model in calculating water budget in real media [11]

4. CONTINUITY EQUATION

Using shallow water is one of the most time-efficient and roughly accurate approaches in simulating surface water continuity equation. It is widely used when groundwater and surface water interaction are took into account. In this situation, shallow water equations are being coupled with three-dimensional equations of groundwater, e.g. Richard's equation. There is vast verity of approaches for solving coupled equations. This approaches could be categorized into three different categories: full coupling, sequential coupling, and loose coupling. In these all categories, equations set to obtain initial and boundary conditions, using continuity equation, and result in the mass transition between surface water and groundwater in different times and locations. In full coupling approach, all equations are solved simultaneously. Sequential coupling is solving equations separately using explicit discretization for at least one of the equations. In loose coupling, one of the surface media on ground media's equations is solved in a time step entirely and the result is used as the input value in the other equation [6].

It is noteworthy that the scale of the problem plays a vital role in model selection. For instance, in a large-scale problem, the river can be modeled with shallow water equations, and the heterogeneity of the river bed can also be ignored [12]. While, in a small-scale problem, the river depth changes and bed permeability in different parts of the river will have significant effects on the final results that can no longer be ignored [13]. Figure 5 shows the scale effects on the key parameters in modeling groundwater surface water interactions.

Some of the models, such as GeoSphere and MIKE SHE, have very complex modeling which requires high-resolution input data. As a result, they are best suited for small-scale problems. On the other hand, models such as CATHY, ParFlow, and SWAT-MODFLOW only take necessary physical processes into account that makes them time efficient models which is suitable for large-scale or long-term problems [14].

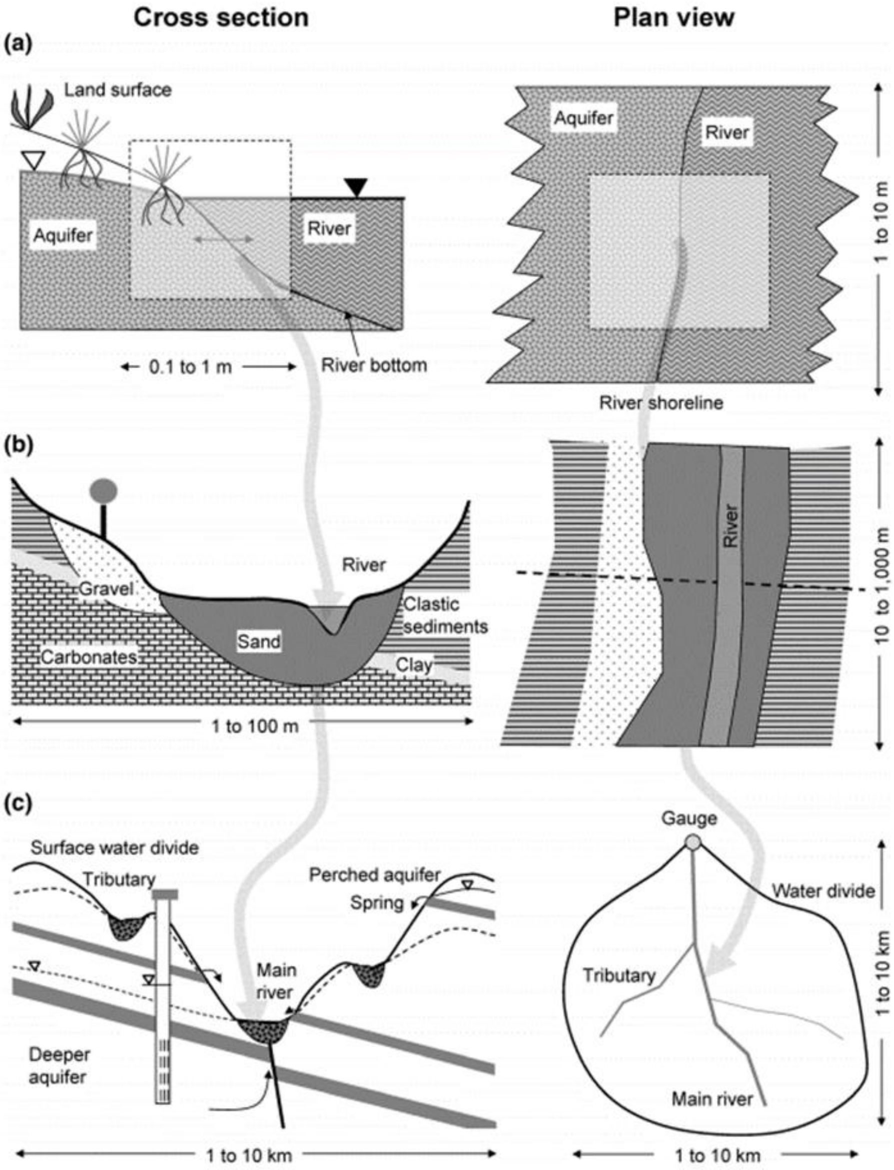

Figure 5. a) Point scale. b) Regional-scale. c) Basin-scale (or sub-basin scale). Depending on the scale, modeling can include several surface water and groundwater[12].

ParFlow, solves the equations with full coupling approach, using mass and pressure conservation to calculate the interaction of the surface water and groundwater [15]. CATHY solves equations based on sequential coupling approach. This model using variable boundary conditions that result in infiltrates or discharge the mass from the groundwater zone and changes the storage of the surface water [16]. SWAT-MODFLOW is coupling two separate models of SWAT and MODFLOW and using their results to solve the integrated system of groundwater and surface water [14].

The equations, which are used in ParFlow, are three-dimensional Richard's equations in groundwater and the kinematic wave approximation in the Saint-Venan equations in the channel. In this model, Richard's equations are discretized centrally in space with a finite difference method. Time steps of this model have been implicitly discretized in backward. The kinematic wave equation has been spatially discretized using upwind finite volume method and Time step discretization is backward and Eulerian. Surface water boundary conditions are determined by assigning critical depth to downstream flow and gradient to the upstream flow, which obtains flow and discharge respectively [15]. Using the equation in this model is shown in equations 4-7:

$$S_S S_w \frac{\partial \psi}{\partial t} + \phi \frac{\partial S_w}{\partial t} = -\nabla . q + q_s \quad (4)$$

$$q = -K_s K_r \nabla(\psi - z) \quad (5)$$

$$\frac{\partial \psi_s}{\partial t} = \nabla . (\psi_s \vec{v}) + q_r(x) \quad (6)$$

$$S_{f,i} = S_{0,i} \quad (7)$$

Where Ss is specified storage coefficient, Sw=Sw(ψ) is the saturation ratio, ψ is underground pressure head, T is time, φ is porosity, is gradient operator, q is discharge based on Darcy- Weisbach equation, qs is sink/source term, Ks is hydraulic conductivity tensor, Kr=Kr(ψ) is the relative function of hydraulic conductivity, ψs is pressure on the river bed, v is depth average velocity of the river, qr is discharge based on the rain, Sf,i and S0,i is the gravity force and friction based on the slope respectively ,in which i demonstrates x and y coordinates.

As it is mentioned before, ParFlow applies boundary conditions to surface water only. In this method, by adding a discharge term to Eq.6, the mass exchange between surface water and groundwater could be calculated, which is shown in Eq.8:

$$\frac{\partial \psi_s}{\partial t} = \nabla . (\psi_s \vec{v}) + q_r(x) + q_e(x) \quad (8)$$

Then the pressure continuity in the highest groundwater cell, i.e. the boundary of surface water and groundwater, is obtained by assigning the pressure head ψ in Eq.4 to ψs, which is the lateral average of the river bed head. Eq.9 shows the described process:

$$P = \psi_s = \psi \quad (9)$$

Hence, the exchange rate between surface water and groundwater is calculated in this model.

The equations used in CATHY model, are three-dimensional Richard's equations in groundwater and the diffusion wave approximation in the Saint-Venan equations in the channel. In this model, Richard's equations have been discretized with the finite element method using the Galerkin approach, also time steps have been implicitly discretized in backward. The diffusion wave equation has been discretized in time and place using the MAD method [16]. Using the equation in this model is shown in equations 10-11:

$$S_S S_w \frac{\partial \psi}{\partial t} + \phi \frac{\partial S_w}{\partial t} = -\nabla . [K_s K_r(\psi)(\nabla \psi + \eta_z)] + q_{ss} \quad (10)$$

$$\frac{\partial Q}{\partial t} + C_k \frac{\partial Q}{\partial S} = D_h \frac{\partial^2 Q}{\partial S^2} + C_k q_s \quad (11)$$

Where, ηz=(0,0,1)T, qss is distributed sink/source, that being minus indicates the sink and being positive indicates the source, Q is discharge across the channel, CK is the velocity of the kinematic wave, s is the river or channel bed's slope. Dh hydraulic release, and qs is the mass exchange ratio between surface water and groundwater, that recharge of the groundwater is indicated by the positive sign and the discharge of the groundwater is indicated by a minus sign.

In this model, the qs term, which indicates the mass exchange ratio between surface water and groundwater, should be calculated.

Another model used in surface water and groundwater interactions is the SWAT model which is developed by USDA. Various versions of this model have been released so far [17]. This model has been used to solve many water resource issues due to its comprehensive features and open source code [18]. In integrated modeling of surface water and groundwater interactions, the SWAT model can be used to solve surface channel equations. Because this model is incredibly powerful in simulating surface flows. In fact, this model takes various parameters, e.g. as precipitation, temperature, base flow, surface runoff, actual evaporation, and aquifer recharge, into account [14]. Although the SWAT model is capable of modeling flow in porous media, it has been developed for flow just in the root zone [19]. As a result, for simulating groundwater surface water interactions SWAT-MODFLOW is more appropriate. In this model, MODFLOW has been used as a subroutine in the SWAT model for calculating groundwater equations [14]. MODFLOW model solves the groundwater equations with finite difference method [20]. Furthermore, the discretization approach of these two models, i.e. MODFLOW and SWAT, is quite different. As a result, the spatial relationship of these two models in boundary regions between them, which indicates the mass exchange, requiressome modifications in the code of the SWAT model [21]. Also, frameworks such as OpenMI and PCRaster could be used in order to fix this problem [20].

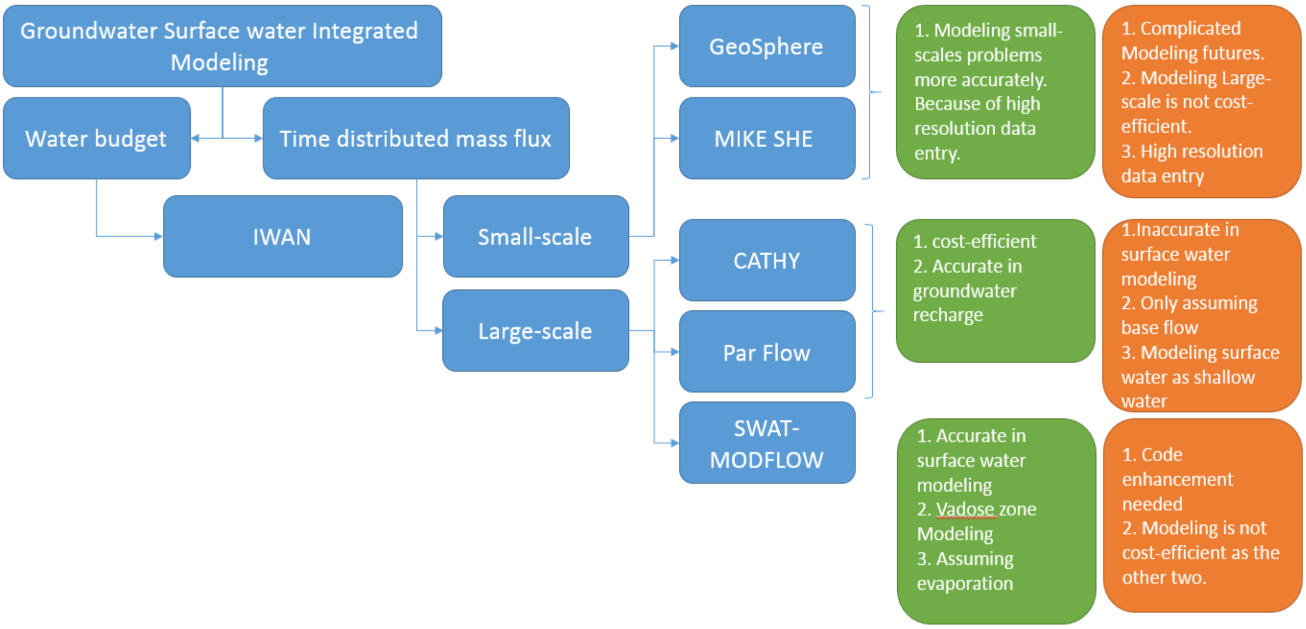

Figure 6.Models of surface water and groundwater interaction flowchart, advantages and disadvantages.

5. CONCLUSION

In the present study, the groundwater surface water interactions using integrated models were discussed. In order to achieve an accurate water balance estimation, which would be possible by considering groundwater and surface water interactions, the field measurement and numerical method were surveyed. Based on the conducted research, using numerical methods yield more acceptable results in comparison with field measurements. Models which solve continuity equations in time and place was also studied. Surface water simulation in these models is much simpler than groundwater equations, which have been simplified due to reducing computational cost.

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