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华北典型地下水大深埋区潜水层垂向补给特征及其给水度

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摘要:针对华北平原地下水大埋深区面积大,而其地下水垂向补给特征及含水层给水度认识不足的问题,以河北栾城试验站附近某研究区为典型区,基于大田试验的水循环模拟,量化了地下水补给及潜水层给水度大小,并探讨了地下水垂向补给特点等关键问题。研究表明:研究区在两个丰水年 2012 年及 2013 年地下水潜在补给量约为 236.6 mm 和 223.5 mm,当年实际补给量约为 144.1 mm 和 129.8 mm,日补给量在 0.37~0.40 mm 及 0.33~0.38 mm;经过厚包气带的迟滞和调节作用,地下水补给过程较为平稳,年际年内差异较小;研究区当前地下水埋深条件下潜水含水层给水度约为 0.03。

关键词:水循环;大埋深;地下水补给;给水度;华北平原

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由于长期的地下水超采,华北平原已经形成大面积地下水大埋深区[1]。大埋深区的地下水补给量,补给特点及含水层给水度的大小等是该区域地下水合理管理的重要依据,也因此引起学者们的重视。Kendy 等[2-3]曾针对华北平原地下水大埋深农田区有无面上的垂向补给这一疑问,利用栾城站的土壤水分观测数据做了 2 m 深度的数值模拟研究;证实了灌溉农田区垂向补给的存在,且跟当年的降水量存在正相关关系。Wang 等[4]及谭秀翠等[5]分别通过示踪剂试验研究了华北平原相关地区地下水潜在补给量的大小。Min 等[6]采用基于大田试验及涡度相关系统的蒸散发观察值采用 Hydrus 进行数值模拟,并采用 CMB 方法,对太行山前平原区灌溉农田的垂向入渗量及厚包气带入渗特征进行了探讨。但目前多数研究关注的是点尺度上在年时间尺度的潜在补给量,也就是厚包气带上部,根系层底部的入渗通量。而由于厚包气带的存在,潜在补给量并不一定在当年补给到地下水。卢小慧等[7]模拟栾城的地下水补给量时采用 EARTH 模型的线性水库模块(概念模型)刻画了厚包气带对入渗补给的迟滞作用。宋博等[8]将降水及潜在蒸发等上边界条件做平均处理,基于土壤水动力学模型做多年模拟,得到长时间尺度上潜在补给量和地下水补给量相等,10 m 以下的入渗水分通量基本稳定在 0.37 mm/d。以上研究多在栾城地区这一典型地下水大埋深区开展,加深了对华北平原地下水大埋深地区潜在补给量及垂向补给过程的认识,且揭示了一些与地下水浅埋深区不同的补给特征。这说明大埋深条件下

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地下水垂向补给的特点及年内分布等问题值得深入探讨。

与此同时，作为水资源评价的重要参数，含水层给水度的评估依赖于对补给过程和开采量的认识。由于补给量和开采量两个方面均存在较大的不确定性，当前对华北地下水大埋深区地下水给水度大小的认识依然不足。一方面，不同学者对该区域的给水度大小认识不一。就栾城地区而言，贾金生等[9]通过 Visual Modflow 模拟研究表明河北栾城的潜水含水层给水度在 0.14～0.17；张兆吉等[10]给出的河北栾城一带的潜水含水层给水度约 0.08～0.12。另一方面，地下水位的持续下降可能会使得区域的含水层给水度发生变化[11]。所以，当前地下水埋深条件下，华北平原大埋深区浅层地下水给水度的大小还有待继续研究。

水循环模拟可以为地下水的补给过程及给水度的量化研究提供有效思路。土壤水文过程联系了地表水文过程和地下水补给过程。土壤墒情也会由于地下水灌溉而变化，从而对蒸散发、地表产汇流及根系层深层渗漏产生潜在影响[12]。水循环各个环节的这种相互联系给相关研究带来较大的不确定性。然而，将蒸散发、地表水、土壤水文过程及地下水运动进行一体化模拟的水循环研究却能利用这种内在联系对各个环节进行相互印证，为研究地下水问题提供一种可行思路。本研究基于在河北栾城开展的大田试验，利用分布式水循环模型 WACM(water allocation and cycle model)和地下水数值模拟模型 MODFLOW 2011.1 进行研究区的分布式水循环模拟，对典型地下水大埋深平原区的地下水垂向补给特点及给水度大小进行探究，以期对地下水大埋深区的地下水资源科学管理提供参考。

1　研究区与研究方法

本研究的基本方法是基于大田试验的数值模拟。大田试验是与中科院栾城站沈彦俊研究员课题组合作在栾城站开展。研究区位于华北平原山前平原区，井灌农业发达，由于长期地下水超采形成地下水大埋深条件，研究期内(2012—2013 年)其潜水埋深在 40～45 m 波动。该区域在华北平原地下水大埋深区有较好的代表性。研究区属太行山山前平原区地质单元，滹沱河冲洪积扇亚区。该亚区可分为 4 个含水岩组：第Ⅱ含水组(底板埋深在 60～120 m)在第Ⅰ含水组(底板埋深 12～20 m)完全开发后成为主要开采段位。第Ⅱ含水层组底部由以亚黏土/亚砂土构成的稳定隔水层与第Ⅲ含水层组隔开，可视为潜水含水层[9]。第Ⅲ含水层和第Ⅳ含水层组为承压水，第Ⅳ含水层组底板埋深在 308～421 m[9]。该区域的潜水水位下降与灌溉农业发展关系密切[13]。该试验中，对研究区(690 375 m^2)典型农田包气带土壤水分动态(0～9 m 深度土壤负压及 0～15.2 m 深的土壤体积含水率)以及相关气象因素等进行监测。包气带土壤水分监测布设的具体介绍可参考文献[6]及文献[14]。此外，在研究区的四个方位布设了监测井(粮站、张村、站内大院及范台)进行潜水(第Ⅱ含水组)水位动态监测。该研究区内的农田由 15 口抽水井开采浅层地下水进行灌溉。

灌溉量是除降水以外重要的水分输入。为使灌溉量尽量准确，研究中主要土地利用类型冬小麦—夏玉米轮作农田的灌溉量评估方法如下。根据土壤水分动态及当日是否有降水发生共同判断当日是否进行了灌溉。土壤水参数先基于降水事件后的土壤水分动态率定。基于实验中前期对灌水量的观测和调查，预设不同作物及生育期的灌水量，在率定过土壤水参数条件下进行模拟，去调试预设的灌溉量，使灌溉后的土壤水分动态模拟结果得到观测结果的验证，此时的灌水量应能较好反映真实灌水情况。

以联合应用 WACM 模型和 MODFLOW2011.1 的方式实现研究区分布式水循环模拟，并利用大田试验进行验证。

1.1　WACM4.0 及其土壤水动力学机制重构

WACM 模型系列是流域/区域自然—人工复合水循环模拟模型[15-16]，当前最新版本 WACM4.0[17-18]在渭河流域、河套灌区等地得到应用和验证。WACM4.0 对土壤水文过程的模拟采用的是基于水势梯度估算各层水分通量的三层均衡法[18]。该方法虽然有计算效率高，参数少等优点，适用于大区域/流域的水循环模拟，但难以刻画地下水大埋深地区土壤水分运动的动力学特征，而垂向土壤水文过程正是该区域水循环的重要环节。因此，本研究先建立可进行表土蒸发、作物蒸腾及土壤水分动态模拟的一维土壤水动力学模型，再将其作为土壤水动力学模块耦合到 WACM4.0 中，模拟各计算单元的垂向土壤水文过程；并对该模块

进行变时间步长和变空间步长等处理,降低土壤水动力学模拟的时间,满足分布式水循环模拟的时效需求(WACM4.0 土壤水动力学模块构建详见文献[19]及[20])。经过改进的 WACM 模型能反映土壤水文过程的动力学特征,在大埋深地区的适用性得到显著提升。

1.2　WACM 与 MODFLOW 的单向耦合

本研究基于 WACM 模型对灌溉等人类水资源开发利用活动有较好的刻画这一长处及 MODFLOW 模型在地下水运动模拟的优势,采用 WACM4.0 与 MODFLOW2011.1 的单向耦合实现研究区水循环模拟。WACM4.0 在平原区采用规则的网格划分(50 m×50 m),分居工地、冬小麦—夏玉米轮作农田区、草皮种植农田区、休耕农田区及核桃种植地等五种土地利用类型。利用 MODFLOW 进行完全一致的网格划分。由于大埋深条件下,地下水不能通过毛细作用上升影响上层土壤,垂向水分通量必然向下,这使得 WACM 与 MODFLOW 的单向耦合成为可能。WACM 模型在气象输入驱动下模拟了地表产流、蒸散发及土壤水文过程,MODFLOW 则承担了水循环过程中地下水运动的模拟。将 WACM4.0 模拟得到的各单元的土壤水下边界的通量作为 MODLFOW 相应单元在相应时段的垂向入渗补给量。

1.3　*初始条件及边界条件*

模拟以 2012 年为参数率定期,2013 年为模型验证期。模拟中最重要的初始条件为包气带的土壤水分剖面。试验中包气带土壤体积含水率及负压监测数据(分别达 15.2 m 和 9 m 深度)不足以提供厚达 40 m 以上的包气带的水分剖面。而包气带的初始水分剖面又必然直接影响入渗量的模拟结果。因此采用试算的方法来得到模拟期的初始土壤水分剖面。通过给不同深度赋予给定负压值来预设初始状态,到模型中进行模拟,实现土壤水分重分布,得到其初始土壤水分剖面。分别预设两种不同的土壤水分初始状态,以 2009—2011 年 3 年作为预热期,以其降水等气象条件驱动模型进行模拟,得到的土壤水分剖面再作为初始条件作为下一次模拟的初始条件,再重复模拟 3 年。模拟结果表明,通过 3 年的预热,实现了全剖面的土壤水分重分布(基于两种不同预设的土壤水分初始状态在预热后得到土壤水分剖面一致)。据此得到的 2011 年末的土壤水分剖面作为 2012 年模拟的初始条件。

地下水头的初始条件以年初研究区四个角上的地下水埋深监测井的数据插值得到。1 月 1 日的地下水水头分布受取水井抽水较少(冬灌一般不发生在 1 月份),水头分布受抽水影响少。根据监测井水头数据绘制其等值线图,得到的研究区地下水流场方向呈西北—东南流向,与研究区所在区域的流场(基于当年石家庄水资源公报)吻合。土壤水模拟的上边界条件是大气边界,下边界条件是给定水头边界,即模拟土柱的最下面的空间节点负压为 0。地下水模拟的边界条件采用给定水头边界。2012 年 1 月 1 日及 2013 年 1 月 1 日的边界单元的逐日水头根据个地下水位监测井的当日水头数据分别插值得到。地下水计算应力期和时间步长均为 5 日。栾城第Ⅱ含水组经由越流补给损失的水量极小(约 3.6 mm/a)[21]。

2　结果与讨论

本研究以 2012 年作为参数率定期,2013 年作为模型验证期。同时基于这两年的模拟结果对研究区地下水垂向补给特点及给水度进行分析。

2.1　*参数率定及模型验证*

模型所涉及的参数较多。对蒸散发及入渗影响较大的有作物系数,根系分布和土壤水分特征参数,对地下水运动影响较显著的有给水度和渗透系数。研究区涉及主要作物有小麦、玉米、种植草皮、及核桃。前两种作物的相关参数在一维土壤水动力学模拟中得到验证。种植草皮的作物系数假设为 1.0,核桃的作物系数参考相关文献[22]得到。包气带土壤水分特征参数参数分层给出,0~6 m 深度采用在一维土壤水动力学模型中率定好的参数,6 m 以下根据研究区深层包气带岩性给出概化参数,研究区内不考虑空间差异(表 1)。该地区包气带深层的岩性以砂夹亚黏土、中细砂为主[20]。研究区水循环模拟所需要率定的核心参数,地下水给水度和渗透系数的最终率定结果为:给水度 0.03,渗透系数 20 m/d。

模型参数率定期和验证期分别为 2012 年和 2013 年。以涡度相关系统 ET 观测值为基准,率定期(2012 年)14 号灌区的 ET 模拟结果为 720.7 mm,相对误差是 5.5%(测量值为 762.9 mm)。日尺度 ET 值(图 1)的纳什系数是 0.662,月尺度 ET 值的纳什系数是 0.943。验证期(2013 年)ET 模拟结果是 708.9 mm,相对误差为 6.0%(观测值为 754.0 mm);日尺度 ET 值(图 1)纳什系数是 0.601,月尺度 ET 值纳什系数是 0.962。

模型参数率定期和验证期典型的冬小麦—夏玉

米轮作单元不同深度的土壤水分模拟结果见图 2 及 3。以均方根误差(RMSE)衡量其误差。

表 1　包气带土壤水分特征曲线参数

深度 /m	岩性	饱和含水率/(cm^3·cm^{-3})	残余含水率/(cm^3·cm^{-3})	饱和导水度 Ks/(cm·min^{-1})	参数 α	参数 n
0.0～0.3	砂壤土	0.36	0.09	0.012	0.010	1.33
0.3～0.9	砂壤土	0.37	0.08	0.010	0.012	1.48
0.9～1.1	粉质黏壤土	0.37	0.10	0.015	0.028	1.29
1.1～1.6	砂壤土	0.33	0.07	0.007	0.023	1.30
1.6～1.9	粉质黏壤土	0.39	0.16	0.008	0.025	1.25
1.9～2.2	黏壤土	0.40	0.17	0.005	0.026	1.12
2.2～2.8	粉质黏壤土	0.40	0.15	0.003	0.018	1.16
2.8～3.2	砂壤土	0.39	0.14	0.016	0.018	1.26
3.2～3.8	粉砂壤土	0.39	0.11	0.080	0.017	1.26
3.8～4.8	砂壤土	0.37	0.11	0.120	0.018	1.18
4.8～5.2	壤砂土	0.43	0.13	0.120	0.015	1.50
5.2～6.0	砂土	0.30	0.05	0.040	0.026	2.20
>6.0	砂夹亚黏土、中细砂	0.30	0.08	0.080	0.012	1.40

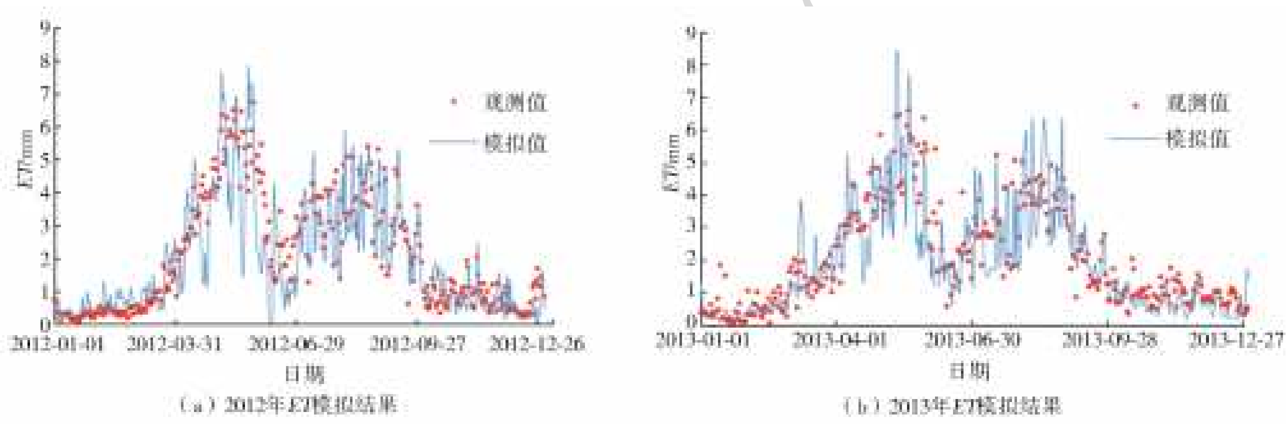

图 1　模型参数率定期(2012 年)及模型验证期(2013 年)*ET* 模拟结果

2.2　地下水垂向补给

2.2.1　点尺度与区域尺度垂向补给量对比

点尺度的(由典型土地利用类型的代表性单元代表)的地下水潜在补给量(指进入深层包气带不再被根系层利用的入渗量)跟区域尺度(研究区)的地下水潜在补给量依然存在一定的差异。此处所指潜在补给量，是指根系层底部(2 m 深度)的水分通量。冬小麦—夏玉米灌溉农田 2 m 深度处水分通量一直是向下的[18]，且草地及休耕地的零通量面更浅，所以经过该深度的入渗量最终会补给到地下水，而不会再返回根系层被利用。模拟结果表明：研究区 2012 年和 2013 年的潜在补给量分别为 236.6 mm 和 223.5 mm；而研究区内主要土地利用类型冬小麦-夏玉米轮作农田的代表性单元 2012 年潜在补给量为 234.3 mm，2013 年潜在补给量 208.9 mm。2012 年研究区潜在补给量(mm/a)与代表单元潜在补给量(mm/a)较为接近(差距为 1.7%)，2013 年研究区潜在补给量为较代表性单元潜在补给量多 12.2%。

研究区内存在不同的土地利用类型，而不同土地利用类型上水循环通量存在显著差异，这会导致点尺度与区域尺度地下水潜在补给量的差别。以 2012 年的水循环通量为例，作为主要土地利用类型的冬小麦—夏玉米轮作地蒸散发达 740 mm，而草皮种植区和休耕地蒸散发分别为 607 mm 和 233 mm；前者的潜在补给量为 237 mm，后两者潜在补给量则分别为 186 mm 和 335 mm。因此，在区域尺度，土地利用类型的结构可能会显著影响区域包括地下水补给量在内的水循环通量的大小。

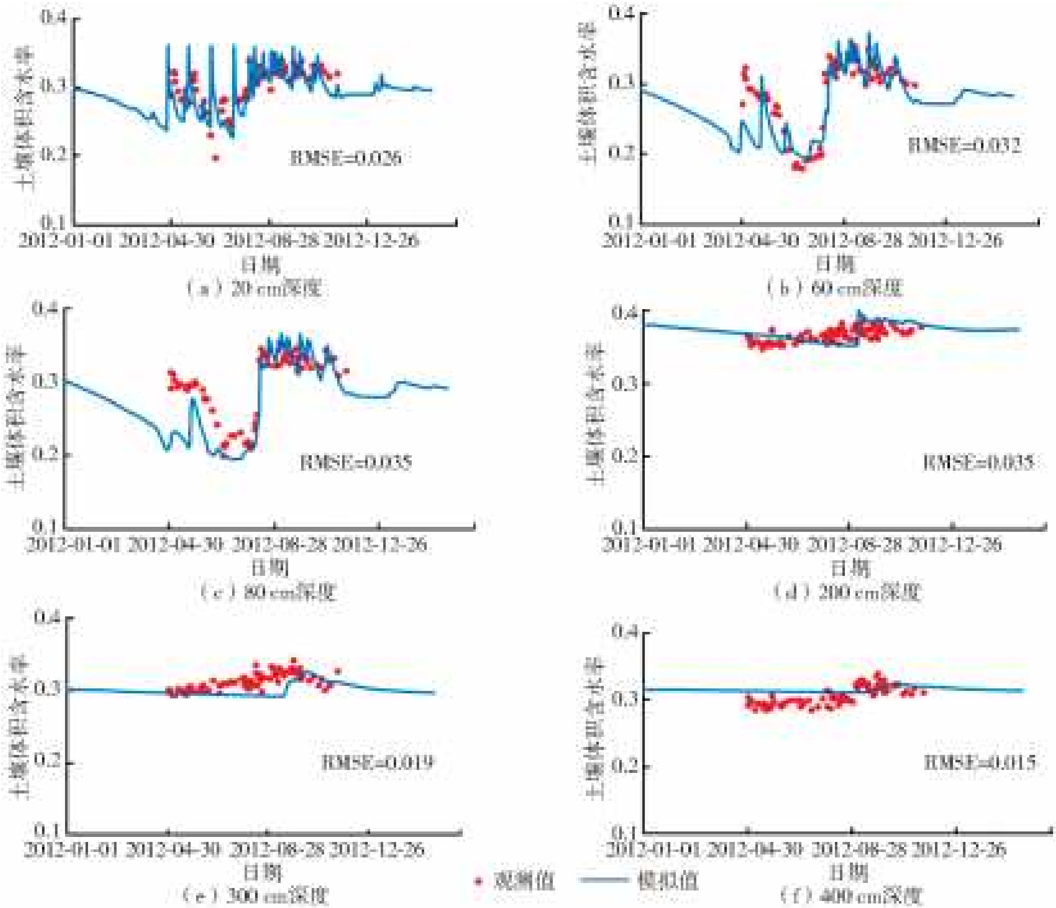

图 2　模型参数率定期(2012 年)不同深度土层土壤含水率模拟结果

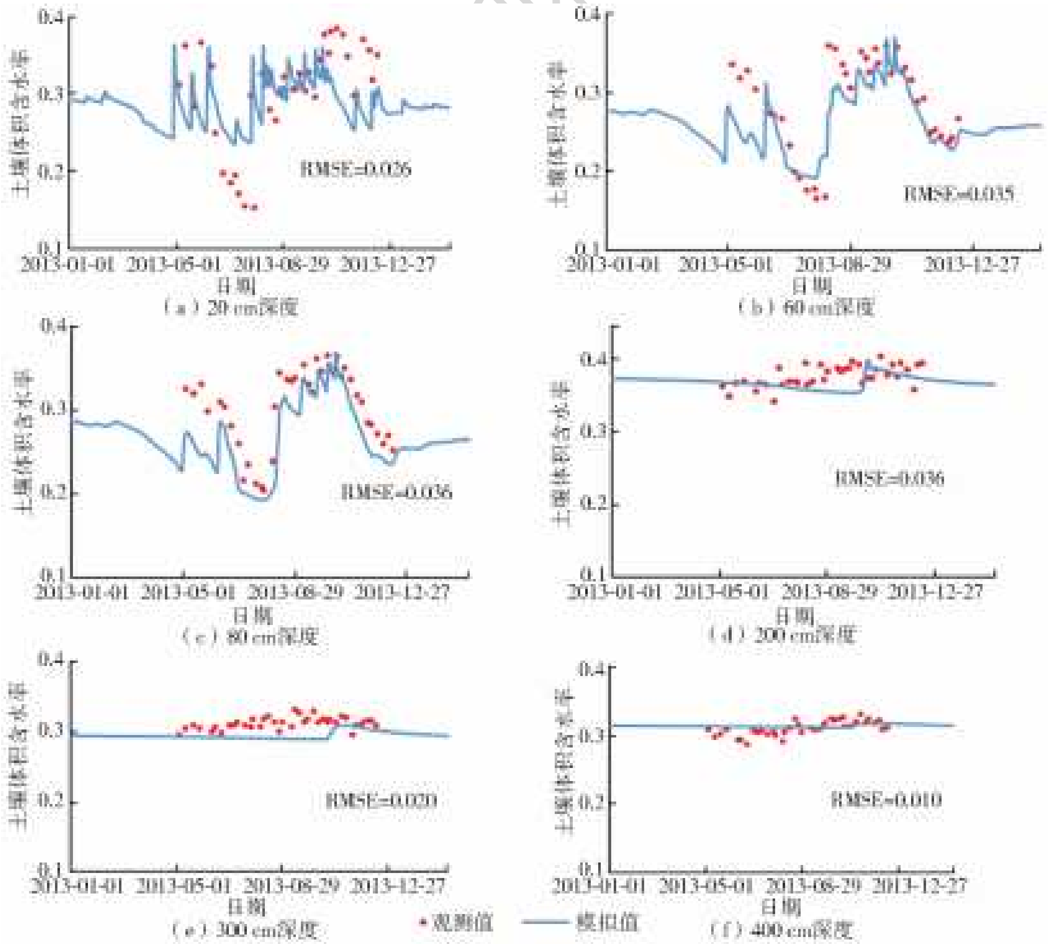

图 3　模型验证期(2013 年)不同深度土层土壤含水率模拟结果

地下水模拟的验证基于研究区一处监测井的地下水水头进行。该监测井位于研究区中部，离灌溉井的距离不少于 200 m。参数率定期及验证期的地下水位模拟结果基本能反映地下水位年内动态，相对来说参数率定期（RMSE ＝ 0.57 m）较验证期（RMSE ＝ 0.61 m）模拟效果（图 4）更好。

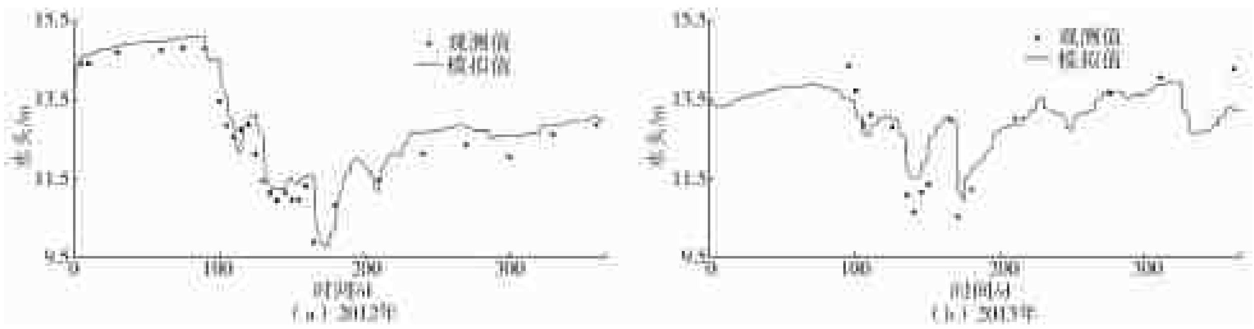

图 4　模型参数率定期（2012 年）及模型验证期（2013）监测井地下水水头模拟结果

2.2.2　研究区潜在补给量与实际补给量

模拟结果表明，2012 年及 2013 年研究区潜在补给量分别为 236.6 mm 及 223.5 mm。而当年地下水补给量（实际补给量）为 144.1 mm 和 129.8 mm。可见，从年时间尺度上看，丰水年地下水补给量是明显小于当年产生的潜在补给量的。长期来看，潜在补给量与实际补给量应相等（暂忽略包气带变厚造成的包气带蓄水量变化[23]），所以在枯水年，地下水补给量应该会大于当年产生的潜在补给量。因此，在大埋深条件下，地下水补给量的年际变异性会较小。

此外，年内的地下水垂向补给过程平缓。图 5 给出了 2012 年潜在补给（根系层深层渗漏）日过程和地下水实际补给的日过程。2012 年，深层渗漏对年内降水分布有明显的响应。深层渗漏主要发生在雨季 7 月至 8 月，而在其他月份较小，其强度在 0.02～14.33 mm/d 波动。而地下水补给强度在 0.37～0.40 mm/d，变幅较小。2013 年类似，地下水补给强度在 0.33～0.38 mm/d。虽然地下水垂向补给过程受包气带岩性影响，本研究中对其深层包气带做了概化，会使得最终模拟的地下水补给量的日过程不完全准确，但模拟结果揭示了入渗过程受包气带调节和迟滞，使得地下水垂向补给较为平稳这一关键特征。

从潜在补给量和实际补给量在年尺度上的差别及深层渗漏过程与地下水补给过程的显著反差可以看出大埋深区包气带对入渗补给的巨大调节和迟滞作用。这是由大埋深地区足够的包气带厚度决定的。包气带的入渗过程会对大气边界做出响应。当水分输入大而蒸散发消耗小时，根系层深层渗漏量大，反之则深层渗漏量小。根系层深层渗漏超过相邻包气带入渗量时，相邻包气带土壤含水率增加，非饱和导水度随之增加；相反，如果深层渗漏量少于该深度包气带入渗量时，该深度包气带处于失水状态，导水度随之下降。这会使一定深度的包气带的土壤水势在年内有一定幅度的变化。但与此同时，相邻包气带容纳一部分来自根系层的深层渗漏被后，其再往下入渗量的变化已经不如根系层深层渗漏的时间变化剧烈，也就是入渗过程被逐层“削峰”。在相对稳定的气候条件下，入渗强度会维持在一定范围内波动。因此，这一波动幅度的有限性决定其影响深度有限。本研究中根系层以下约 3～4 m 深度包气带受其影响，在这之下的包气带则保持相对稳定的土壤水分（水势）条件及较为稳定的入渗强度。

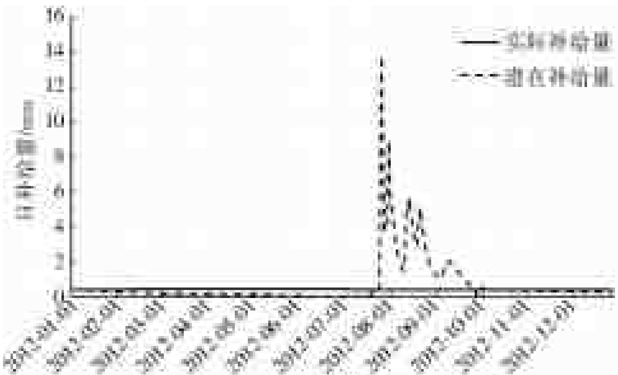

图 5　2012 年地下水实际补给与潜在补给（根系层深层渗漏）日通量过程对比

2.3　给水度

根据参数率定结果，研究区给水度大小约为 0.03。这个结果可能存在一定偏差。偏差主要来自两个方面，一是作为地下水主要源汇项的灌溉开采量并不是完全来自实测，会存在一定偏差。另一个方面是研究区面积较小，研究区对应的地下水含水层并不独立。通过插值得到的边界条件并不能完全代表实际情况。

尽管如此，本研究中给水度率定结果能得到研

究区地下水埋深监测井的水位年内动态变化及灌溉开采情况的印证。栾城地区地下水位以年均 0.85 m(1980—2008 年)的速率下降[24]。但这仅仅是年际的降幅。仅根据年初及年末的地下水位埋深变化和年尺度超采量来估算含水层的给水度可能会忽略山前平原侧向补给量的影响。从年内的地下水位埋深动态看更能反映含水层实际给水度。2012 年,栾城站监测井地下水位埋深从 3 月 21 日的 39.48 m 增加至 6 月 21 日的 45.42 m,地下水位降幅达 5.94 m;与此类似,2013 年,地下水埋深由 3 月 11 日的 40.52 m 增加至 6 月 16 日的 45.3 m,地下水位降幅达 4.78 m。各年地下水位下降最迅速的时段正是年内的灌溉需求最大的时期一小麦生长期和玉米播种期。地下水位动态跟主要作物(冬小麦/夏玉米)的灌溉时间及强度有较好的对应关系(图 6)。3 月中下旬到 5 月这一时段,有小麦春灌、拔节期和孕穗期的灌溉需求;6 月中旬,是夏玉米播种期,会有底墒水灌溉需求。以每年较为固定的 6 月中旬夏玉米播种期底墒水灌溉(约 60～70 mm)[25]为例,研究区站内大院、张村、粮站、旱井等几处埋深监测井地下水位在 6 月中旬均下降 1.39 m 至 3.42 m 不等(平均 2.27 m),而 2013 年同期下降 2.30 m 到 3.19 m 不等(平均 2.55 m),这就说明是研究区水位普遍的下降,而不仅仅是某个监测井受邻近灌溉抽水井抽水漏斗作用的影响。考虑到地下水侧向补给及垂向补给较地下水开采过程均相对缓慢,忽略一次灌水过程中该区域地下水侧向流入、流出及垂向补给的量。若地下水开采 60～70 mm,水位下降 2.4 m(两年均值)计算,则给水度约 0.025～0.029,与本次模拟研究率定结果 0.03 接近。这也就从数值模拟以外的角度佐证了本次模拟研究中给水度率定结果的有效性。这表明关于该地区的潜水含水层在当期埋深条件下的给水度的现有认识可能偏高。

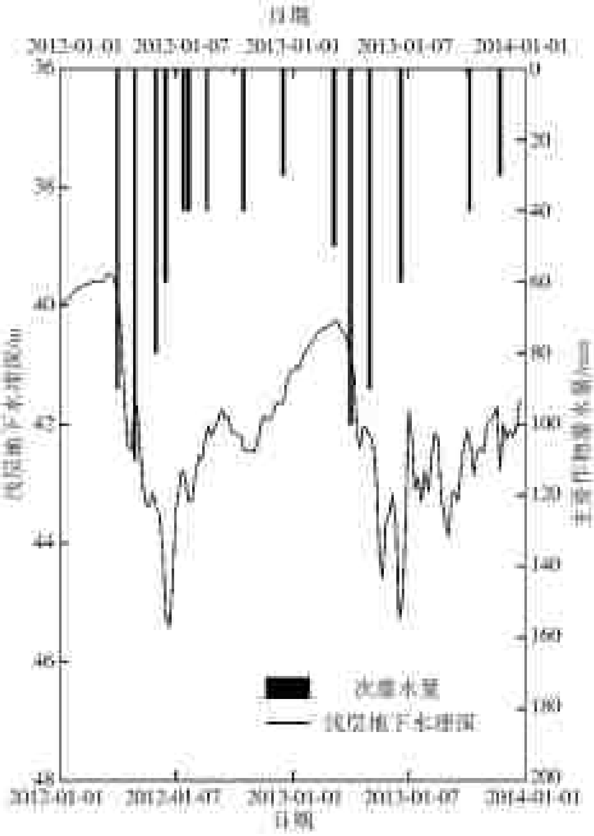

图 6　2012－2013 年栾城站监测井地下水位埋深动态及主要作物(小麦/玉米)灌溉量

3　结　论

本文以河北栾城站研究区为例,尝试采用基于大田试验的水循环模拟的思路研究地下水大埋深地区地下水补给过程特点及给水度问题。研究表明:研究区潜在补给量较典型土地利用类型上点尺度的地下水潜在补给量存在一定差异(2012 年和 2013 年分别达 1.7%和 12.2%),点尺度与区域尺度的入渗量的差异说明了土地利用类型的结构对地下水潜在补给量的显著影响。经过厚包气带对入渗过程的迟滞和调节,地下水补给过程呈现相对稳定的状态,年际年内差异较小;2012 年及 2013 年补给强度在 0.33～0.40 mm/d 小幅波动。大埋深区潜在补给和实际补给过程的显著差异不应该在相关的研究种被忽略。在研究时段埋深(40～45 m)条件下,河北栾城试验站所在区域的潜水含水层给水度约为 0.03,较现状认识水平更低,需引起重视。地下水垂向补给量及给水度存在较大的空间变异性,此外,尽管大埋深区的地下水垂向补给的年际和年内时间变异性较小,但也并不是完全恒定。本研究中的量化结果局限于栾城站试验区在研究期(2012 年及 2013 年)的状态,但其揭示的地下水大埋深区的地下水补给过程的特点对其他地下水大埋深区也有一定的参考价值;此外,本研究所采用的蒸散发-地表水-土壤水-地下水耦合模拟的方法探讨地下水相关问题的思路对其他地区也有可借鉴的意义。

本研究假设大埋深区的垂向补给以活塞流为主,未考虑优先流。此外,研究区范围较小,地下水的模拟受边界条件影响较为明显。今后可在更大的研究范围内开展实验观测,并进行数值模拟。

致谢:感谢甘肃农业大学沈彦俊教授及其团队在中科院遗传与发育生物学研究所农业资源研究中心工作期间对本研究的大力支持。感谢河北地质大学刘振英教授对本研究提供的宝贵意见。

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Research on vertical recharge and specific yield of the unconfined aquifer in a typical deep groundwater areas of North China Plain

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Abstract: The area of regions with a deep groundwater table is expanding in North China Plain (NCP). The characteristics of groundwater recharge and the value of specific yield have not been well studied in NCP. Therefore, an agricultural area near Luancheng Experimental Station, Hebei Province, was taken to study the vertical recharge and the specific yield using distributed water cycle modeling based on a field experiment. Moreover, the groundwater recharge characteristics were also explored. The results showed that in 2012 and 2013, the potential recharge was 236.6 mm and 223.5 mm, while the groundwater recharge was 144.1 mm and 129.8 mm, respectively, in the study area. And the daily recharge rate ranges between 0.370 mm/d and 0.404 mm/d and 0.327 and 0.382 mm/d in 2012 and 2013 respectively. This scenario indicated that the groundwater recharge was relatively stable and the inter-annual and inter-diurnal differences were small due to the regulation and buffering of the deep vadose zone. Besides, the specific yield of the unconfined aquifer was about 0.03.

Key words: water cycle; deep groundwater table; groundwater recharge; specific yield; The North China Plain

Large area with a deep groundwater table has been formed due to long term groundwater over-exploration[1]. The amount and characteristics of groundwater recharge, as well as the specific yield of the aquifer are fundamental bases for local water resources management, which have attracted the attention of researchers. For instance, Kendy et al. conducted a numerical simulation using 2-meter in-depth soil moisture observation data at Luancheng station, to find whether there is vertical recharge in the deep groundwater table cropland area of NCP. The obtained results verified the existence of vertical recharge in the irrigated croplands, which is increasing with the increase of precipitation[2,3]. Wang et al.[4] and Tan et al.[5] investigated the amount of the potential recharge in NCP using tracer experiment. Min et al. studied the annual recharge and percolation characteristics using Hydrus based numerical simulations, eddy covariance and the Chloride Mass Balance (CMB)[6]. Recently, most of studies focus on the annual potential recharge at the point scale, which is the deep percolation at the bottom of the root zone and the upper part of the deep vadose zone. However, the potential recharge may not necessarily reach the aquifer

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due to the depth of the deep vadose zone. Lu et al. depicted the lagging of percolation with a linear reservoir module in the EARTH model, while simulating the groundwater recharge in Luancheng[7]. Song et al[8]. averaged the upper boundary conditions including precipitation and potential evapotranspiration in the soil moisture dynamics modelling, and revealed that the groundwater recharge equal to the potential recharge in the long run, and the water flux maintains 0.37 mm/d at the depth of 10 meter. Most of these studies were carried out in Luancheng, a typical region with a deep groundwater table, which enhanced the understanding of the potential recharge and the vertical percolation process in a deep groundwater table region of NCP. and revealing some differences with the recharge characteristics in regions with a shallow groundwater table. The aforementioned scenario suggested that the characteristics of vertical recharge and its temporal distribution within one year under deep groundwater table conditions required further investigation.

In addition, the estimation of specific yield, an important index in water resource evaluation, depends on the understanding of recharge processes and the amounts of groundwater pumping. However, the specific yield in a deep groundwater region (NCP) is difficult to evaluate because of the uncertainties in recharge and water pumping. But different scholars have different views in the estimation of this specific parameter. Taking Luancheng for example, Jia et al. [9] estimated the specific yield of unconfined aquifer to range from 0.14 and 0.17 based on simulation in ModFlow, while this index was estimated to vary from 0.08 to 0.12 by Zhang et al. [10] Moreover, the decreasing groundwater table might lead to change in the specific yield[11]. Therefore, under current conditions of groundwater depth, more studies are required to get a better estimation of specific yield in the NCP.

Water cycle simulation can provide an effective perspective for the research of groundwater recharge process and quantification of specific yield. The soil hydrological process is related to surface hydrological processes and groundwater recharge process. Moreover, soil moisture also altered due to groundwater irrigation which has a potential impact on hydrological process including evapotranspiration, surface runoff, and deep percolation[12]. This kind of interrelation of each link of water cycle brings great uncertainty to related research. However, the integrated simulation of evapotranspiration, surface water, soil hydrological process and groundwater movement can make use of this internal connection to verify each link, which provides a feasible way to study groundwater problems. Based on the field experiment in Luancheng, Hebei province, this study used a distributed water cycle simulation model Water allocation and Cycle model (WACM) and groundwater numerical simulation model, MODFLOW version 2011.1, to investigate the characteristics of vertical recharge and the specific yield in a typical deep groundwater table region. This study may contribute to groundwater management in regions which have deep groundwater table.

1　Study area and methods

The primary method is a numerical simulation based on a field experiment. The field experiment was carried out with the cooperation of the research group supervised by Dr. Shen Yanjun of Luancheng Station, Chinese Academy of Science. The study area was located in the piedmont area of NCP, with well-developed irrigated agriculture. Long term groundwater over-exploitation led to a deep groundwater table, which ranged between 10 to 45 m from 2012 to 2013 in the study area. This area was a typical deep groundwater table in NCP. The study area is belonged to Hutuo River Pluvial Fan and the geological unit piedmont plain of Taihang Mountain. This Pluvial Fan included four water-bearing formation. The second formation with the floor depth of 60 to 120 m became the one being developed after the most upper one, whose floor was with a depth of 12 to 20 m, being exhausted. The floor of the second formation was consist of loam and sandy loam, which formed a stable confining bed for the second formation and the third one. Therefore, the second formation could be regarded as an unconfined aquifer[9]. The third and the fourth formation were confined ones, and the floor depths of the fourth one ranged between 308 to 421 m[9]. The decline of the groundwater table was closly related to the local irrigated agriculture development[13]. In this experiment, the soil moisture dynamics in a typical irrigated cropland were monitored including meteorological factors. As for the soil moisture dynamics, the soil water suction at the depths as far as 9 meter and the volumetric soil water content were measured, the design and layout of which was introduced in detail by and Wang et al. [14] and Min et al. [6]. In addition, monitoring wells were distributed in the four corners (which are Grain Station, Zhang Village, Courtyard, and Fantai) of the study area, to record the dynamics of the groundwater table for the second formation. The cropland was irrigated with fifteen pumping wells in this study area.

Irrigation is the most critical water input besides precipitation. To make the amount of irrigation more reliable in the simulation, an estimation method is carried out for the irrigation amount on cropland with winter wheat and summer corn rotation, the dominating land use. First, whether it had been irrigated or not was judged based on the soil moisture dynamics and the rainfall on the day. Secondly, an estimated amount of irrigation was given based on the previous available records and irrigation survey. Then simulation was carried out to examine whether the soil moisture dynamics could coincide with the observed ones under the conditions of the calibrated soil water parameters after precipitation. The estimated irrigation amount could be adjusted to make the simulated soil moisture dynamics coinciding better to the observation. The irrigation estimation after adjustment will be closer to that in reality.

The distributed water cycle simulation was carried out with the coupling of WACM and MODFLOW, and validated by the data from a field experiment.

1.1 WACM4.0 and reconstruction of soil moisture module

WACM series are distributed hydrology model which simulates the water cycle in coupling nature-human system[15-16]. The latest WACM4.0 was verified in the Weihe River basin and Hetao irrigation District[17-18]. In WACM4.0, soil hydrological processes are simulated by a three-layer balance method in which water fluxes between two layers are estimated based on the water potential gradient[18]. This method does not suffice to depict the characteristics of soil moisture dynamics in region which have a deep groundwater table, where the vertical soil hydrological process is the most important aspect. Therefore, a 1-D soil moisture dynamics model coupling soil evaporation, crop transpiration, and soil moisture dynamics was established and integrated with WACM4.0 as the soil moisture module, to simulate the vertical soil hydrological processes in each grid. Also, some techniques including varying temporal steps and spatial step were adopted to reduce the time consumption, making it more suitable for distributed hydrological modeling. The detailed information about WACM can be found in Li et al[19-20]. The modified WACM 4.0 can depict the characteristics of soil hydrologic processes, improving its applicability in regions which have a deep groundwater table.

1.2 One-way coupling of WACM and MODFLOW

This study was carried out using one-way coupling of WACM and MODFLOW to simulate the water cycle in the study area, considering the human water resource development activities including irrigation. Regular grids of 50 m×50 m size were used for the plain area in WACM. And the land cover was divided into five types, i.e. built-up area, cropland with the rotation of winter wheat and summer maize, cultivated grassland, fallow field, and cropland cultivating walnut. The same grids were used in the MODFLOW. The water flux in the deep vadose zone will be always downward with a deep groundwater table because the capillarity from groundwater would not affect the upper soil layers. This cloud make the one-way coupling of WACM and MODFLOW reasonable. WACM simulated the surface runoff, evapotranspiration, and soil moisture processes using the meteorological forcing. The MODFLOW simulated the groundwater dynamics in the water cycle. The water fluxes at the lower boundaries of the soil column for each grid, which were the vertical recharge, imported to the MODFLOW as the upper boundary conditions.

1.3 Initial and boundary conditions

The year 2012 was taken as the calibration period, while 2013 was used as the validation period. The most important initial condition for the simulation was the soil moisture profile for the deep vadose zone. During experiment, the monitoring data of volumetric soil water content and soil suction which reach the depth of 15.2 m and 9 m did not sufficient to provide the soil moisture profile of the vadose zone of more than 40 m depth. However, the initial soil moisture profile imposed direct impact on the simulation results of the recharge. Therefore, pre-heat training was used to obtain the initial conditions. Three-year period from 2009-2011 was used to simulate the two different given initial soil moisture profile. The final condition was taken as the new initial soil moisture profile and the three-year pre heat simulation was repeated with these new soil profile. The final conditions at the end of 2011 from two different given initial soil moisture profiles coincide with each other. This showed a reliable initial soil moisture profile for the start of 2012.

The initial groundwater head was given with the interpolation based on the monitoring data. The groundwater head distribution at the start of a year (Jan-1), would not be substantially impacted by pumping because there was hardly irrigation during this period, which made the interpolation a feasible way to represent the spatial distribution of the initial groundwater head. The contour of the groundwater head obtained with this method indicated that the groundwater flow from northwest to southeast, coinciding with the reported flow field by the Water Resource Bulletin of Shijiazhuang. The upper boundary condition was an atmospheric condition for the soil moisture simulation, while the lower boundary condition was given head boundary. The soil suction was assigned to be zero for the lower boundary of each column. The upper boundary for the groundwater dynamics simulation was given head boundary. The groundwater heads of boundary grids were obtained with interpolation based on the data of monitoring wells. The stress period and the time step were both assigned to be 5 days. The leakage from the second formation to the third one was insignificant, which was about 3.6 mm per year, estimated by Shao et al[21].

2 Results and discussion

This study took the year 2012 as the calibration period, while 2013 was used as validation period. The analysis of the vertical recharge characteristics and the specific yield were based on the results of those two years.

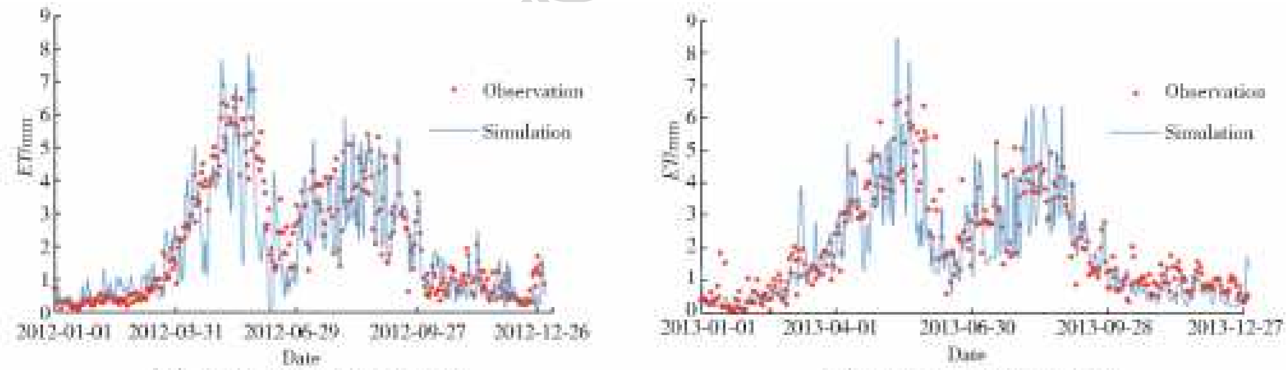
2.1 Calibration and validation

Many parameters were involved in this model. The most important parameters for the evapotranspiration and recharge include crop coefficient, root distribution with depths, and hydraulic parameters of soil layers. Specific yield and conductivity matter in the groundwater dynamics. In the study area wheat, maize, cultivated grass, and walnut were the main crops. Parameters for the first two crops were calibrated in the 1-D soil moisture dynamics simulation. The crop coefficient of cultivated grass was assumed to be 1.0, while that of walnut for each month was estimated based on Zhang et al[22]. The hydraulic parameters were given for each soil layer in the vadose zone. Particularly, the parameters calibrated in the 1-D soil moisture dynamics simulation were adopted for the depth of 0 to 6 m, while the vadose zone deeper than 6 m was generalized as one layer and their parameters were given based on the dominating soil type (Tab. 1), sand with sandy clay and medium-fine sand[20]. The spatial variability of the soil hydraulic properties and groundwater parameters were ignored. Two key parameters specific yield and conductivity were calibrated to be 0.03 and 20 m/d, respectively.

Tab. 1 The hydraulic parameters of soil layers at different depth of the vadose zone

Depth/m	Soil type	Saturated water content/ ($cm^3 \cdot cm^{-3}$)	Residual water content/ ($cm^3 \cdot cm^{-3}$)	Saturated conductivity(Ks)/ ($cm \cdot min^{-1}$)	α	n
0. 0～0. 3	Silt loam	0. 36	0. 09	0. 012	0. 010	1. 33
0. 3～0. 9	Silt loam	0. 37	0. 08	0. 010	0. 012	1. 48
0. 9～1. 1	Silt clay loam	0. 37	0. 10	0. 015	0. 028	1. 29
1. 1～1. 6	Silt loam	0. 33	0. 07	0. 007	0. 023	1. 30
1. 6～1. 9	Silt clay loam	0. 39	0. 16	0. 008	0. 025	1. 25
1. 9～2. 2	Clay loam	0. 40	0. 17	0. 005	0. 026	1. 12
2. 2～2. 8	Silt clay loam	0. 40	0. 15	0. 003	0. 018	1. 16
2. 8～3. 2	Silt loam	0. 39	0. 14	0. 016	0. 018	1. 26
3. 2～3. 8	Sandy loam	0. 39	0. 11	0. 080	0. 017	1. 26
3. 8～4. 8	Silt loam	0. 37	0. 11	0. 120	0. 018	1. 18
4. 8～5. 2	Loamy sand	0. 43	0. 13	0. 120	0. 015	1. 50
5. 2～6. 0	Sand	0. 30	0. 05	0. 040	0. 026	2. 20
>6. 0	Sand with sandy clay, medium fine sand	0. 30	0. 08	0. 080	0. 012	1. 40

The calibration periods and validation period are the year 2012 and 2013 respectively. Taking the (evapotranspiration) ET as observation data from the eddy covariance system as ground truth. The relative bias was 5. 5% in the data during the calibration period. The simulated and observed values were 720. 7 mm and 762. 9 mm, respectively. The Nash coefficient of daily data was 0. 662, while for monthly data it was 0. 943. For the validation periods, the relative bias was 6. 0%. The simulated and observed values were 708. 9 mm and 754. 0 mm, respectively. The Nash coefficient of daily data was 0. 601(Fig. 1), while for the monthly data it was 0. 962.



(a) Simulationresults of ET in 2012
(b) Simulationresults of ET in 2013

Fig. 1 The ET simulation results during calibration period (year 2012) and validation period (year 2013)

The simulation results of soil moisture for the typical grid with a rotation of winter wheat-summer maize during the calibration and validation periods are shown in Fig. 2 and Fig. 3. The simulation error was evaluated with RMSE (root-mean-square error).

Groundwater dynamics simulation was validated with the observation data from a monitoring well in the central area of the study area, which was more than 200 m far away from all the irrigation wells. The simulation results coincide with the observed groundwater table dynamics, while the performance during calibration period was a little better than that in validation period, with RMSE 0. 57 m and 0. 61 m, respectively (Fig. 4).

2. 2 Vertical groundwater recharge

2. 2. 1 Comparison between recharge at point scale and regional scale

There were differences between the potential recharge at the point scale and the regional scale. The point scale was represented by typical grid

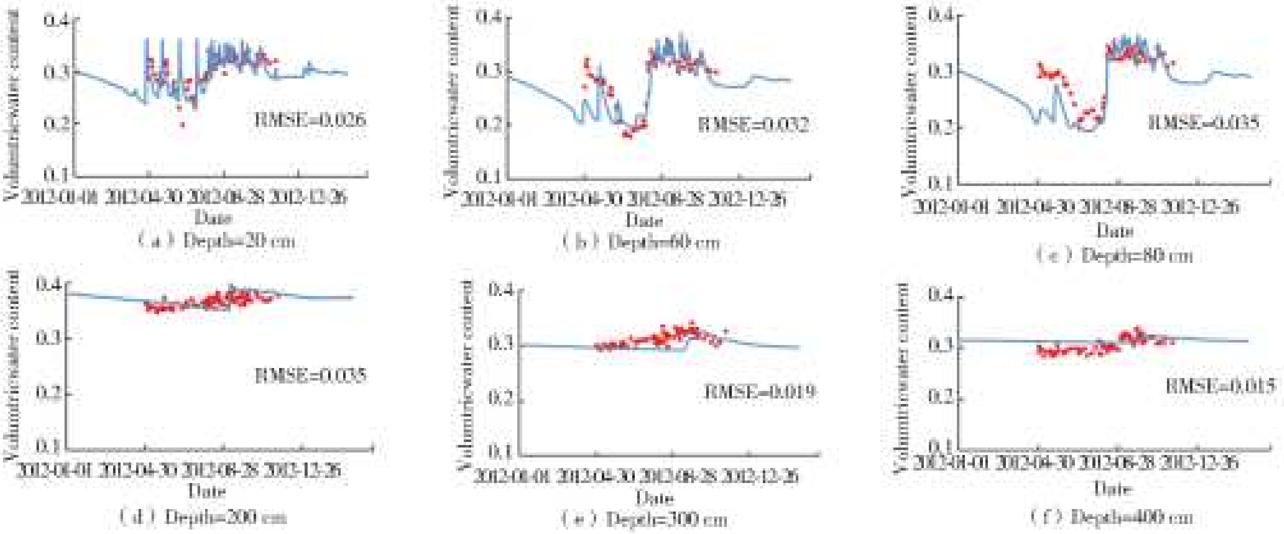


Fig. 2　The soil moisture simulation results during calibration period (year 2012)

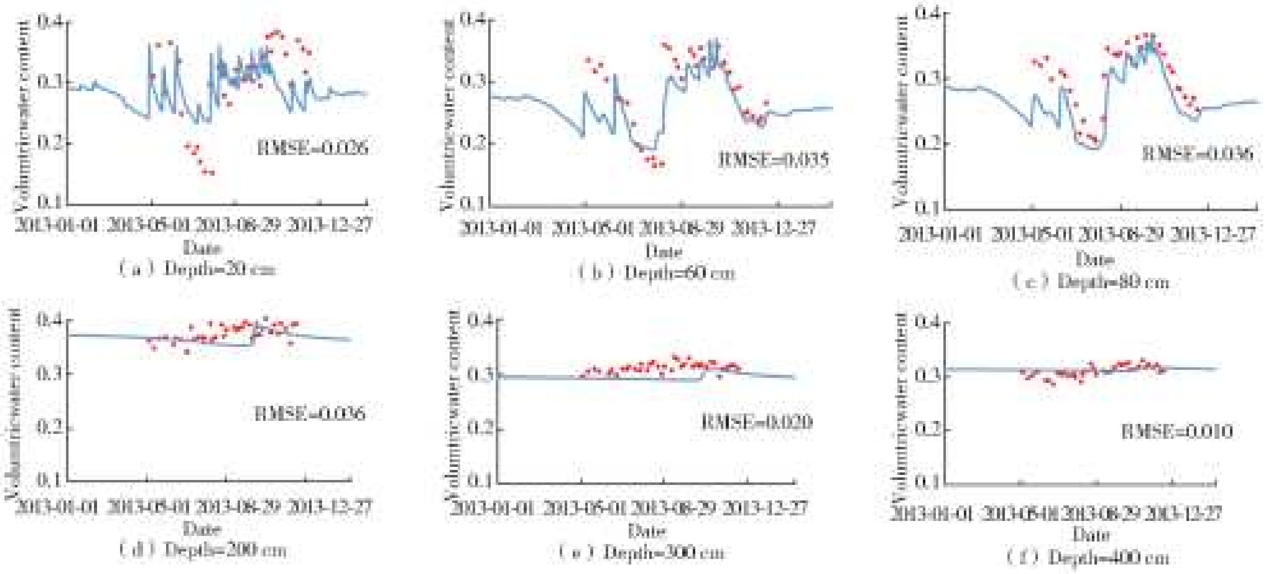


Fig. 3　The soil moisture simulation results during validation period (year 2013)

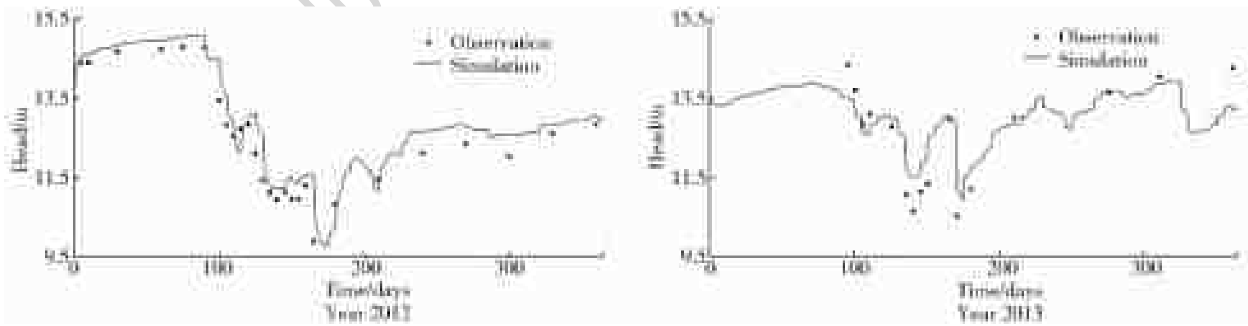


Fig. 4　The soil moisture simulation results for the year 2012 and 2013

while the regional scale was total study area. The so-called potential recharge, was the water flux at the bottom of the root zone at the depth of 2 m. The water fluxes at the depth of 2 m under cropland with winter wheat-summer maize rotation were always downward[18], while the zero-flux planes under cultivated grass and fallow field were shallower. Therefore, the percolation at depth (2 m) would finally reach the groundwater as recharge, without upward movement to the root zone. The simulation results showed that: (1) the potential recharge of the study area was 236.6 mm and 223.5 mm in the year 2012 and 2013; (2) the potential recharge of the typical grid with the dominating land cover, winter wheat-summer maize rotation was 234.3 mm and 208.9 mm in the year 2012 and 2013. The potential recharge in the total study area and a typical grid was close to each other in 2012 with a gap of 1.7%, while the former was 12.2% percent larger than the later in 2013.

The different land-use types in the study area account for the differences between the potential recharge at point scale and region scale since the water fluxes were different under different land-use types. Taking the water fluxes in the year 2012 as an example, the evapotranspiration over the cropland with rotation of winter wheat and summer maize, the dominating land use type were reached 740 mm, while for over cultivated grassland and fallow field were 607 mm and 233 mm, respectively. Correspondingly, the potential recharge was 237 mm over the former land use, while those were 186 mm and 335 mm over the latter two kinds of land-use types, respectively. Therefore, the structure of the land use types significantly impacted the water fluxes including groundwater recharge over regional scale.

2.2.2 Potential and actual recharge to groundwater

Simulation results showed that the potential recharge at the study area was 236.6 mm and 223.5 mm in 2012 and 2013, while the recharge reaching the groundwater table was 144.1 mm and 129.8 mm respectively. The recharge to groundwater was significantly less than the potential recharge during wet years. In the long run, the potential recharge and the recharge to groundwater should be equal, if the increase of storage brought by the increase of depth of the vadose zone was ignored[23]. Therefore, it can be inferred that the recharge to groundwater should be larger than the potential recharge in dry years. Based on this, the annual variation of recharge to groundwater will be small in regions with a deep groundwater table.

The vertical recharge within a year is stable. Fig. 5 presents the daily process of potential recharge, or the deep percolation, and recharge to groundwater during 2012. The deep percolation responded to the seasonal variation of precipitation. Deep percolation focused on July and August, which was rainy season, while it remained small in other months. The deep percolation rate ranged between 0.02 to 14.33 mm/d. Meanwhile, the recharge to groundwater ranged between 0.37 to 0.40 mm/d. In 2013, the situation was similar, with the recharge rate ranging between 0.33 mm/d and 0.38 mm/d. The vertical infiltration processes were impacted by the hydraulic properties of the vadose zone, which was generalized in this study, thus affecting the accuracy of the daily process of groundwater recharge. Despite this, the simulation results revealed the key characteristic of recharge, being stable, which was after the lagging and smoothing of percolation in the deep vadose zone.

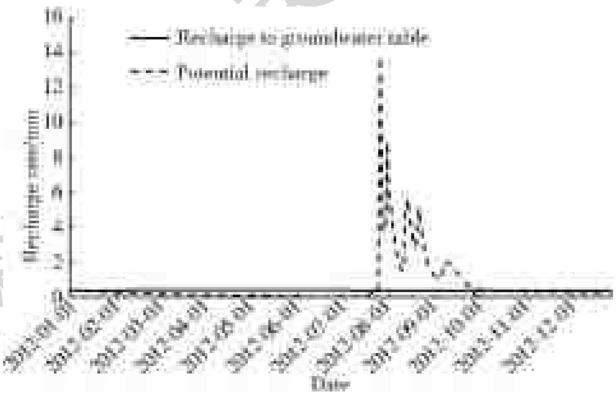


Fig. 5 The comparison between the groundwater recharge and the deep percolation in 2012

The significant comparison between the yearly amounts and the daily processes of potential recharge and the recharge into groundwater during the study period indicated the smoothing and lagging effect on recharge from the deep vadose zone. This was because, the depth of the vadose zone was sufficient for the process. The percolation will respond to the atmospheric boundary. The deep percolation would be large when the water inputs, including precipitation and irrigation, were large and the evapotranspiration was relatively small. For the soil layers below the root zone, when the percolation from the root zone was more than the percolation into lower soil layers, the soil moisture will increase, with the hydraulic conductivity increasing correspondingly. On the other hand, when the percolation from the root zone was less than the percolation into lower soil layers, the soil moisture will decrease, with conductivity decreasing. This will make the soil moisture to some depth of the vadose zone varying with some ranges. Moreover, the percolation into lower soil layers will be more stable with some of the percolation from the root zone being absorbed by the layers below the root zone, which indicated that the percolation was forced to be more and steadier layer by layer. The percolation rate will vary within a certain range with a given climate condition. The limitation of a variation range decided that there will be a limitation to the soil depth that was affected. In this study, soil moisture and percolation at the vadose zone about 3-4 meter below the root zone was affected by these variations, while in the deeper part of the vadose zone remain relatively steady.

2.3　Specific yield

Based on the calibration results, the specific yield of the study area was 0.03. There might be some bias with this result. These biases might two aspects. The first one was the irrigation amount, the main source item in groundwater simulation, did not come from field measurement. The second one was the study area, relatively small, do not cover an independent aquifer. The boundary conditions based on interpolation could not totally represent the actual situation.

Though, the calibration result of specific yield could be verified by the dynamics of the groundwater table with the irrigation pumping. The groundwater table had declined with an annual rate of 0.85 m between 1980 and 2008[24]. However, this was the inter-annual change. It would overlook the lateral recharge if the specific yield were estimated based on interannual groundwater table change and annual groundwater pumping amount. In 2012, the groundwater table depth increased from 39.48 m on March 21 to 45.42 m on June 21, with a change of 5.94 m. Similarly, it increased from 40.52 m on March 11 to 45.3 m on June 16 with a change of 4.78 m in 2013. The periods with most immense irrigation demand, the maturing periods of winter wheat and the sowing period of summer maize were the periods when the groundwater table rapidly declined. Fig. 6 indicated that the groundwater table dynamics coincided well with the periods and amounts of irrigation for the dominating crop, winter wheat and summer maize. From the middle and latter part of March to May, there was demand for spring irrigation, elongation stage irrigation and booting stage irrigation of winter wheat. In the central part of June, there were irrigation demand for summer maize before sowing. Taking the irrigation for summer maize before sowing as an example, the irrigation amount range between 60 mm to 70 mm[25]. The decline of the groundwater table at these monitoring wells ranged fbetween 1.39 m to 3.42 m during the middle part of June 2012, with an average being 2.27 m. Those ranged between 2.30 m to 3.19 m at the same period in 2013, with the average being 2.55 m. The consistent decline of groundwater table in all the monitoring wells indicated that the groundwater table declined in the whole study area, rather than declining in some areas close to the irrigation wells. The lateral recharge, discharge and vertical recharge were insignificant during an irrigation event given that all these processes are much slower compared to the groundwater pumping. Then, the specific yield was estimated to range from 0.025 to 0.029, with the average groundwater decline being

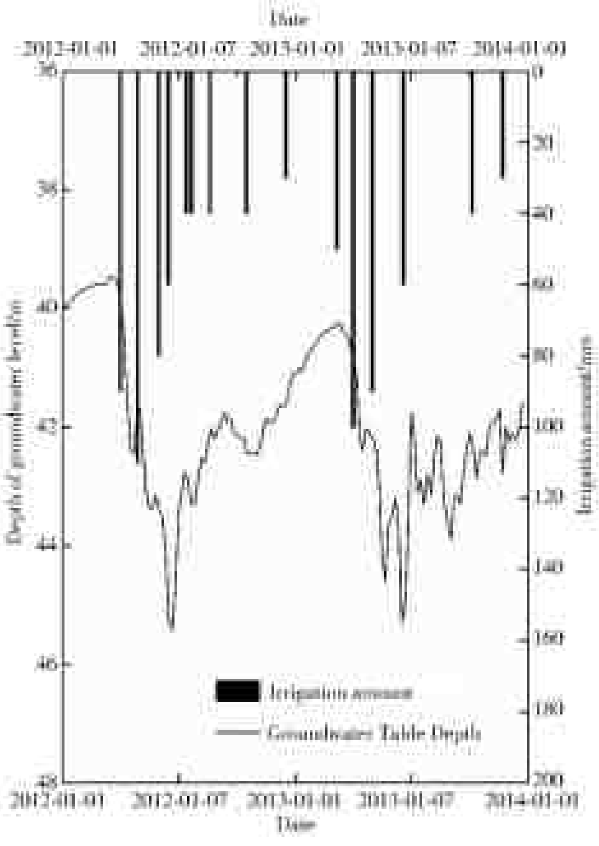


Fig. 6　The groundwater table dynamics at the monitoring well and irrigation amounts of the dominating crops

2.4 m after 60～70 mm irrigation pumping in the same period in 2012 and 2013. The result was very close to the calibration result of a specific yield, 0.03. This verified the calibration result of specific yield from a perspective other than numerical modeling. Therefore, the current evaluation of the specific yield in this area might be too high.

3 Conclusions

Taking Luancheng Station as a case study, this paper adopted a new methodology, water cycle modelling based on field experiment, to investigate the vertical recharge characteristics and the specific yield in regions with deep a groundwater table. The results showed:

(1) the potential recharge of the study area differed from that of the typical unit with dominating land use type, and the former is 1.7% and 12.2% higher than the later one in 2012 and 2013 respectively; The difference of potential recharge at point scale and region scale indicated that the structure of land use will impose significant impacts on potential recharge;

(2) the recharge to groundwater was stable with insignificant temporal variations, due to the lagging and smoothing effect from the deep vadose zone; the vertical recharge rate ranged from 0.33 mm/d to 0.40 mm/d in 2012 and 2013; The differences between the potential recharge and the recharge to groundwater deserve our attention;

(3) the specific yield of the study area at Luancheng was about 0.03 when the groundwater table depth was between 40 and 45 m. This was much lower than the current evaluation, which needed to be taken seriously.

In addition, the vertical recharge was not constant though it showed small temporal variations. The quantification results based on the conditions inthis particular study area in 2012 and 2013, but the recharge characteristics revealed implications for regions with similar groundwater table conditions. Moreover, the adopted methodology such as coupling simulation of evapotranspiration, surface water, soil moisture and groundwater dynamics, provided a reference for groundwater study in other regions.

This study assumed the dominating vertical recharge being piston flow, overlooking the preferential flow. Additionally, the simulation of groundwater dynamics was sensitive to the boundary conditions, with the study area being relatively small. Similar field experiments and numerical modeling required to be done in a larger study area in the future.

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