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Present-Day Risk of Occasional Extreme Hydrological and Hydrogeological Events

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ABSTRACT

Extreme hydrological and hydrogeological events have appeared in different climate zones. In this study we presented extreme events in the frigid zone(Russia) and the subtropical zone (Taiwan). In the example of frigid zone, extreme hydrological events on the rivers of European part of Russia are closely related to the hydrological regime transformation answering recent climate changes. Rivers in this region used to be traditionally attributed to the Eastern-European type with well-pronounced seasonal flood wave and quite low flow period during summer and winter. During the last twenty years the role of the occasional floods became more and more important. Number of winter floods, connected with thaws rose dramatically, in the same manner as summer flash floods. Due to results increase in natural runoff regulation, does not reduce frequency of extreme events, in some regions it raises. In the example of subtropic zone, the large demand on water resources causes the groundwater overpumping in Taiwan to result in serious subsidence of plain area. Clarifying the causes and identifying the contribution of compaction from different pumping sources is a challenge for a multi-layer aquifer system. An integrated model was applied to Yuanchang, in the center of the Yunlin subsidence area, Taiwan. Data of groundwater level and compaction at aquifers 2 and 3 in dry-season periods were used to explore the pumping effects on compaction. The results show that single-layer groundwater users are responsible for the large-area compaction and that significant local compaction can be attributed to multi-layer users. Constraining multi-layer pumping activities and reducing the amount of groundwater exploitation are required to mitigate the subsidence in Taiwan.

KEY WORDS: extreme hydrological and hydrogeological event, subsidence, climate change.

INTRODUCTION

The occurrence of extreme hydrological and hydrogeological conditions associated with either high or low water content creates risks and economic losses associated with water use. Such extreme events may not be rare in occurrence but typically affect large areas, resulting in a damage in several economic sectors. In the frigid zone such as Russia only in the last 5 years there were three disasters like that. In 2010, the abnormal processes in the atmosphere and a breakdown of a typical atmospheric circulation led to deep water shortage that affected the most part the European territory of Russia. More than 40 temperature records were broken. The drought resulted ina large number of forest fires. Smog in Moscow on some days has reduced visibility to 100 m (Fig. 1 a). Due to long-term water supply that was stored in reservoirs, large losses were avoided (Alekseevskiy, Frolova et al., 2013). Water deficit was observed only in the Don basin and the Ural region. Thus, in the Belaya river basin navigation was completely closed for two months. On the Northern Dvina from the end of July till the end of August water level was below normal by 60-120 cm. However, navigation was guaranteed by intensive and costly dredging.

Fig. 1.a) Smog in Moscow, 2010 (D. Zverev's photo) b), c) Catastrophic flood in 2013 Oka river (N.Frolova's photo and A. Kamensky's photo) d) Flooded by Rybinsk Reservoir city Mologa, which came out of the water in 2014 (Y. Rassulin's photo)

Next situation arose in winter 2012 - 2013, when snowpack in central Russia reached a height of 80 cm and more. This led to formation of a spring flood of very low probability. Water levels on the Oka River, for example, rose to a level close to dangerous. Most of the valley was flooded, including all levels of the flood plain. In dozens of settlements water came right up to the houses (Fig. 1 b,c). In 2014, by contrast, it was a very warm and unstable winter. Water storage in the snowpack was minimal, resulting in the early start of dry season. The Volga reservoirs replenishment schedule was disrupted. The old city Mologa that was flooded by Rybinsk reservoir years ago, started to appear from under the water (Fig. 1 d).Navigation on the upper Volga and Okawas stopped in July, causing multimillion losses to the cruise tourism business. According to RosHydromet (Federal Hydrometeorological Service),number of dangerous hydrolometeorological events doubled from 150-200 in the early 1990s to 350-450 by the end of 2000's (Fig. 2). Potential loss of each hazard can be up to 1.3-1.6 billion euro according RIHMI – IDC (International Data Center). Under these circumstances, studying the prerequisites for the formation of extreme hydrological events is one of the most urgent problems in Russian hydrology.

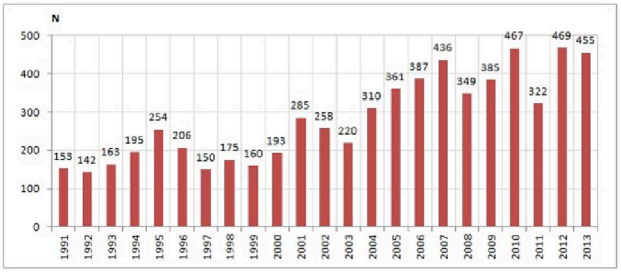

Fig. 2.Number of dangerous hydrometeorologicalphenomena (http://www.meteorf.ru)

Fig. 3.The map of representative basins (the numbers of the basins corresponds to Table 1)

Different climate zone may expose different hydrological condition. In the subtropical zone such as Taiwan the normal annual temperature on the land surface was found to increase in the beginning of the 21st century by 0.6oC on the land as a whole, 0.9oC in the territory of Russia, and even 1.1oC in Taiwan. The rate of the rise is uneven and shows a tendency of acceleration in recent years. Just in the last two decades the average temperature has been elevated one degree Celsius in Taiwan. The deviation also appears in the precipitation in addition to the temperature. On one hand, drought has become more frequent and longer lasting. For example, 2015 is the most serious drought year in recent 68 years in Taiwan. On the other hand, the highest precipitation record is renewed more frequently and unexpectedly. For example, Typhoon Kalmaegi in July 2008 broke the one-hundred-year rainfall intensity record and brought one third of Taiwan's average annual precipitation (about the world average annual precipitation) within consecutive twenty four hours. These symptoms of climate fluctuation tend to induce instability in the utilization of surface water resources. With an erratic supply of surface water resources, it is clear that Taiwan's groundwater resources will be increasingly relied upon in the future. The huge demand on groundwater results in subsidence in plain area.

Study Area

The extreme hydrological cases are introduced in Russia. The European territory of Russia is a vast territory with an area of about 4 million km^2. This region includes basins of river Volga, Don, the Northern Dvina, Pechora, Ural, and many others. Extreme hydrological events on the rivers of European part of Russia are closely related tothe transformation of the hydrological regime due to the recent climate changes. Rivers in this region used to be traditionally attributed to the Eastern-European type with well-pronounced seasonal flood wave and quite low flow period during summer and winter. Currently, the ratio between runoff indifferent periods of the year is changing dramatically. Statistical and spatial analysis of data from 300 gauging stations shows, that these changes are represented by an increase in low flow and a reduced runoff during high-water period. For example, the low-flow period runoff of Don river increased almost twice from the first to the second half of the XX century (Dzhamalov R.G.,et al, 2013). A similar situation is typical for the Oka and the Upper Volga, where the growth in low flow is about 50-70% (Dzhamalov R.G., et al., 2013). In the Kama basin changes are less significant, about 15 – 30%. For the northern rivers such as the Northern Dvina and Pechora, increased runoff in the low-water period is less pronounced and ranges from 5 to 15%. For Mezen and Neva these changes are almost insignificant (Dzhamalov R.G., et al., 2014). Along with the increase in runoff in winter and summer a drastic reduction in the seasonal flood runoff is observed. The decline is most evident in those regions where the low flow period runoff is growing the most. In the Don basin the seasonal flood weakly stands out among many winter and spring flash floods, and the maximum discharge is halved (Kireeva M.B. and Frolova N.L., 2013). Degradation of the seasonal flood is observed in the Volga basin too, the maximum discharges there reduced by 20-40%. Thus, there is an equalization of intra-annual flow distribution, and an increase in the natural runoff regulation rate. The details of these changes are discussed in (Frolova N.L., et al., 2014).The main goal of this work was to determine the impact of water regime changes on the occurrence of extreme hydrological events.

In the subsidence study, Yuanchang is located in the middle of the southern part of the Choshuishi alluvial fan, which is the largest groundwater reservoir in Taiwan. The alluvial fan has a multi-layer aquifer system composed of Holocene sediment. According to subsurface lithology and hydraulic conductivity data of the fan, the proximal, mid, and distal sections are distinguished from east to west. Four main aquifers are delineated, namely aquifers 1, 2, 3, and 4, from top to bottom (CGS, 1997). The aquifers are mainly composed of gravel or coarse sand and are separated by an aquitard of clay and silt. The proximal part of the Choshuishi alluvial fan is mainly composed of gravel; aquifer layers cannot be distinguished in this region. The vertical alternation of gravel/sand-dominated units and clay-dominated units reflects cyclic variations in the sea level, with fluvial coarse material deposited during sea-level low stands and fine material deposited during transgressive high stands. The depths below the ground surface (BGS) for aquifers 1 to 4are0 to 32 m,64 to 152 m, 170 to 212 m, and below 238 m, respectively. The thickness of aquifer 4is uncertain because not all wells penetrate this aquifer. The estimated thickness is around 24 m based on the available well logging data. The natural direction of water flow in the aquifer system is essentially westward. The aquitards serve as barriers for interlayer movement of groundwater. Leakage may appear through aquitards. Although aquifers are defined, interbedding clay within the aquifers is clear and thought to be the major material that causes compaction of aquifers. Thick aquitard 1 appears at the Yuanchang station and the upper alluvial fan. Thin aquitard 2 separates aquifers 2 and 3 with groundwater flows between the two aquifers. Many field tests were performed to determine the hydraulic conductivities and storage coefficients for the aquifers in the Choshuishi alluvial fan. Very few hydrogeological properties were measured for the aquitard. Hsu et al. (2006) applied harmonic analysis to acquire the hydraulic conductivity of an aquitard in the Choshuishi alluvial fan. Low hydraulic conductivities were found, being three to five orders of magnitude lower than those of adjacent aquifers. The major identified groundwater users are Taiwan Yunlin Irrigation Association (TYIA) and Taiwan Water Corporation (TWC).The main goal was to identify the contribution of water users to subsidence on the extreme hydrogeological events.

MATERIALS AND METHODS, RESULTS

For an objective assessment of the impact of hydrological events on the economy the integral criteria are often used. They are based on the comparison of observed characteristics with the "threshold" values that were selected. According to the difference between the two, the impact of the event on people's lives and economy can be estimated. It is also common to take into account not only the actual difference, but the period of time for which the characteristic was exceeding the limit. These calculations allow to estimate the total deficit or excess of water. The resulting number corresponds with the duration of the phenomenon and represents an integral index of "severity" of the event. As a threshold it is most common to use the water discharge of specified repeatability. In this work, the analysis was made based on the threshold numbers of 10% and 90% probability discharges. 19 hydrological stations with the area more than 20,000 km2 were chosen in different geographical zones for the analysis. The analysis was based on the monthly discharge data (Fig. 3).

Unit discharge, corresponding to the upper threshold values, varies according to changes in the zonal runoff. The highest values were found in the north-east of European Russia in the basins of Usa, Pechora, Vishera river – 49, 42, 42 liters per second per km2 (l/s·km2), respectively. The average value for the north river is from 20 to 30 l/s·km2and decreases from north-east to south-west. Adjacent to the south basin of the Upper Volga, Oka and Ugra thresholds are reduced to 12-16 l/s·km2. Kama River basin have significantly higher thresholds of runoff - an average of about 20-23l/sec·km2. Minimum values are typical for the Don basin, especially Medveditsa river (less than 4l/s·km2). In the spatial distribution of low threshold observed a similar pattern. Low threshold (10% probability) more than 2 l/s·km2is typical for northern rivers of ETP. In the basins of the Upper Volga and Oka, it is reduced to 1.7 l/s·km2and Vetluga and Moksha – 1 l/s·km2. In the Kama basin, the rate increases to 1.6-1.7 l/s·km2. In the Don basin the unit discharge threshold is reduced to 0.5-1 l/s·km2 (Table 1). For northern rivers the number of cases that exceeds the high threshold value is between 60 and 75, in the basin of the Oka, Moksha and Ugra - about 70. In the Kama basin it increases reaching 80-87. Don basin number of exceedances is about 65 cases. The number of deficits on the contrary increases from 35 - 40 in the north to 50 - 60 in the south of European Russia. An interesting fact is that the number of extremely low and extremely high-water periods associated with each other: the more the river there is an extremely low monthly discharges, the more there is in it and extremely high discharges (Fig. 4).

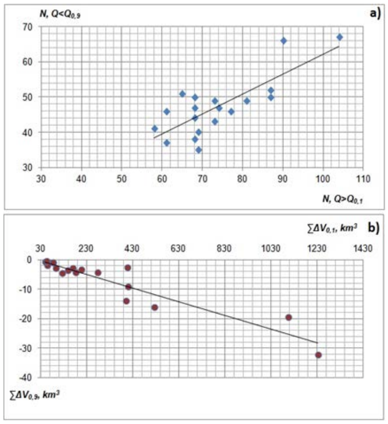

Fig. 4.Relationship between the number of periods of extremely low and extremely high flow (a) and total volume deficit and surplus (b)

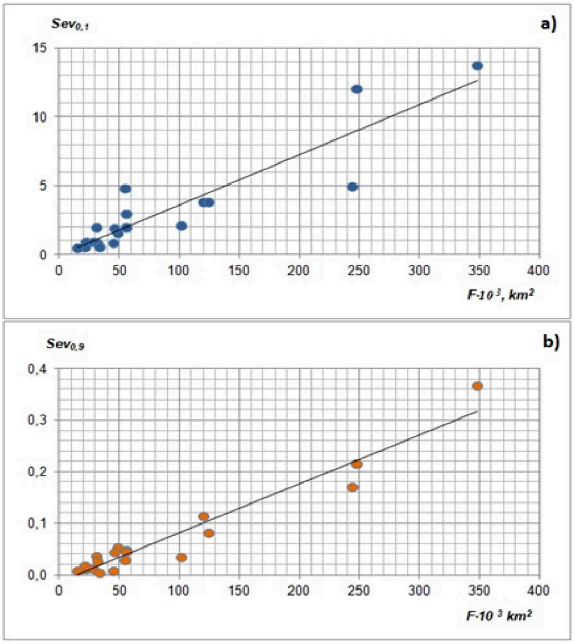

Fig. 5.Dependency between the "Severity" and catchment area for 0,1 (a) and 0,9 (b) probability

The volume of deficit is clearly related to the volume of surplus, the correlation coefficient is greater than 0.9 (Fig. 5). Thus, every river, has some integral rate of "extreme", which characterizes the amount of water shortages and the number of highs. The more "extreme" is the water regime of the river, the more it's runoff as abnormally low or high. In world practice in such estimates is often used so-called index of severity (Sev). It is the ratio of the excess or shortage of water for the duration of this phenomenon.

$$\mathrm{Sev_i} = \frac{\Delta \mathrm{V_i}}{\mathrm{T}} \tag{1}$$

where Sev - indicator of severity, ΔV - the deficit or surplus, km3, T - the duration of abnormally low or high values of discharge, days, i– probability, percent.

The data obtained enable to calculate severity of the conditions for excess and deficiency of water (Table 1). At extremely high flow the severity of the studied rivers varies from 0.55 - 0.57 in the Don basin and the Upper Volga to 13.7 in the basin of the Northern Dvina. There is a close relationship between the severity and the catchment area (Figure 6 a). With the increase in the catchment area severity rises quite rapidly. At extremely low flow rates the severity varies from 0.1 in the basin of the Upper Volga and the Don to 0.37 in the basin of the Northern Dvina. Dependence is also a linear - the higher the catchment area, the greater the severity of water shortages, observed on the river (Figure 6 b).

For some regions there is a tendency to group the most extreme years in time. So, in the basins of the northern rivers, the most severe water shortage occurred in 1938 – 1945 and 1965 - 1975 years were extremely abounding. Water scarcity is observed on these rivers also in the 2000s. In the basin of the Upper Volga were extremely dry 1945, 1950, 1967-1969, and abounding - 1966, 1974, 1947-58 years. But last case of the extreme shortages was 1977, according to calculations. So, conditions of 2010 and 2014 are completely normal for water regime. Tributaries of the Volga behave somewhat differently. On the Oka, Ugral, Moksha water shortage is mainly observed in the 1937 - 1939 years, and the high-water period was in 1958, 1970, 1979 - 1981. Last deficits observed here in 1973 - 1975 (except p. Moksha, which tends to Kama river basin). By the rivers of the Kama basin water shortage observed in the 1920s - 1940s, and water excess – in 1960 - 1970s and early 1990s. However, even in recent years (2006, 2008) as well as from 1976 - 1977 some deficiencies are allocated here.

Table 1 Characteristics of extreme events for 10 % and 90% probability threshold values

River	Station	Q>Q$_{0,1}$					Q<Q$_{0,9}$				
		q$_{0,1}$, l/s·km^2	N	ΔV, km3	T, month	Sev	q$_{0,9}$, l/s·km^2	N	ΔV, km3	T, month	Sev
N. Dvina	Ust-Pinega	23,8	74	16,7	1,22	13,73	2,1	47	-0,7	1,94	-0,37
Onega	Porog	20,2	61	2,4	1,21	1,99	2,4	37	-0,1	2,00	-0,05
Mezen	Malonisogo-rskaya	29,6	77	3,6	1,22	2,97	2,3	46	-0,1	1,98	-0,05
Pechora	Ust-Cilma	41,5	73	15,1	1,26	12,02	2,0	43	-0,5	2,09	-0,22
Sukhona	Kalikino	21,6	61	2,0	1,31	1,55	1,5	46	-0,1	1,78	-0,05
Usa	Adzva	49,5	69	5,9	1,23	4,78	1,2	35	-0,1	2,40	-0,03
Vetluga	Vetluga	22,3	58	1,2	1,28	0,92	1,0	41	0,0	1,79	-0,01
Volga	Staritsa	16,1	90	0,7	1,23	0,55	1,7	66	0,0	1,65	-0,02
Moksha	Shevelkovskiy Majdan	9,2	69	1,2	1,29	0,93	0,7	40	0,0	2,28	-0,01
Oka	Gorbatov	11,6	68	6,9	1,41	4,92	1,7	47	-0,3	2,00	-0,17
Ugra	Tovarkovo	12,4	73	0,6	1,23	0,45	1,6	49	0,0	1,78	-0,01
Belaya	Birsk	17,4	104	5,0	1,32	3,82	1,9	67	-0,2	2,12	-0,11
Vishera	Ryabinino	42,3	68	2,5	1,26	1,97	3,6	38	-0,1	2,21	-0,04
Vyatka	Vyatskie Polyani	19,5	87	4,7	1,24	3,81	1,6	52	-0,2	2,10	-0,08
Kama	Bondug	23,3	81	2,3	1,20	1,90	1,7	49	-0,1	2,04	-0,04
Ufa	Verkhnij Suyan	18,5	87	1,1	1,33	0,82	1,6	50	-0,1	2,24	-0,03
Don	Kazanskaya	6,3	68	3,1	1,43	2,15	1,0	44	-0,1	2,14	-0,04
Medvedica	Archedinskaya	4,2	68	0,8	1,43	0,57	0,4	50	0,0	1,90	-0,01
Khoper	Besplemya-novskiy	6,7	65	1,3	1,49	0,87	0,5	51	0,0	1,88	-0,01

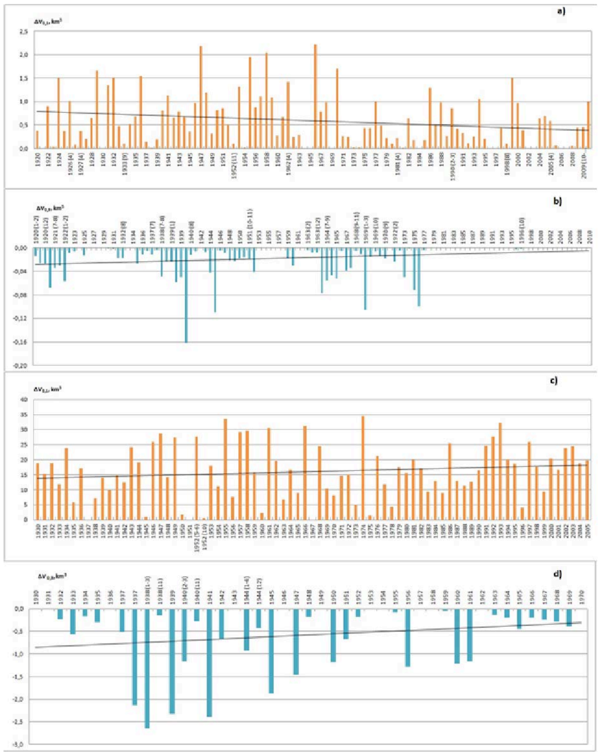

Fig. 6 Volume of surplus (a) and deficit (b) for the Volga – Staritsa and volume of surplus (c) and deficit (d) for the N.Dvina – Ust-Pinega

Dynamic of the extreme rates is also very interesting. Northern rivers are characterized by smooth increase in elevation above the thresholds, and the reduction in deficits. The frequency of occurrence of extreme water discharges is reduced from 80 - 100% at the start of observations up to 20 - 30% at the moment. For instance, the deficits on the Northern Dvina, mostly observed in the 30s - 40s. After that began a steady decline in the frequency of water shortages, but the duration of the deficits, on the contrary increased from 1 - 2 months to 3 and sometimes 4, and its volume decreased. On Onega and Mezen trends are very different from other rivers. Here comes the decline in excess water and increase indeficits. In the basin of the Upper Volga different picture is observed. There is a marked decrease in volume of extremly high water events and simultaneous decline in deficits - the water regime significantly leveled. To the east of the region - in Kama basin, different pattern observed, similar to the trend in the north ETR. There is a smooth increase in water excess and decline in deficits. Low-flow period becomes less deep and volume of seasonal-flood conversely increases. The southern part of the ETP, Don and Oka shows the most obvious changes. Surplus reduced at times, and deficits in general no longer occur since 1975-77.

For the extreme hydrogeological events, an integrated model was constructed. A two-aquifer/one-aquitard system (Neuman and Witherspoon, 1969) was adopted to model the groundwater in the multi-layer aquifer system. Neuman and Witherspoon (1969) used Laplace and Hankel transforms and inverted the results. The analytical solution of drawdown in the pumped aquifer is:

$$s_1(r,t)=\frac{Q_1}{4\pi T_1}\int_0^\infty\left(1-e^{-y^2\overline{t}_{D_1}}\right)\cdot\left\{\left[1+G(y)\right]J_0\left[\psi_1(y)\right]+\left[1-G(y)\right]J_0\left[\psi_2(y)\right]\right\}\frac{dy}{y} \tag{2}$$

where $\overline{t}_{D_1}=t_{D_1}(r/B_{11})^4/(4\beta_{11})^2$, $t_{D_i}=K_it/S_{S_i}r^2$ is the dimensionless time for pumping at the *i*-th aquifer, $J_0(x)$ is a zero-order Bessel function of the first kind, $G(y)=M(y)/F(y)$, $\psi_1^2(y)=\left[N(y)+F(y)\right]/2$, and $\psi_2^2(y)=\left[N(y)-F(y)\right]/2$. Functions $M(y)$, $N(y)$, and $F(y)$ are respectively defined as:

$$M(y)=\left[\frac{(r/B_{11})^4}{\beta_{11}^2}-\frac{(r/B_{21})^4}{\beta_{21}^2}\right]\frac{1}{16}y^2-\left[\left(\frac{r}{B_{11}}\right)^2-\left(\frac{r}{B_{21}}\right)^2\right]y\cot y \tag{3}$$

$$N(y)=\left[\frac{(r/B_{11})^4}{\beta_{11}^2}+\frac{(r/B_{21})^4}{\beta_{21}^2}\right]\frac{1}{16}y^2-\left[\left(\frac{r}{B_{11}}\right)^2+\left(\frac{r}{B_{21}}\right)^2\right]y\cot y \tag{4}$$

$$F(y)=\sqrt{M^2(y)+\left[\frac{2(r/B_{ij})(r/B_{ij})y}{\sin y}\right]^2} \tag{5}$$

Where $B_{ij}=\dfrac{1}{\sqrt{K'_j/K_iH_iH'_j}}$ and $\beta_{ij}=r/4H_i\sqrt{K'_jS'_{s_j}/K_iS_{s_i}}$

Drawdown in the aquitard is:

$$s'_1(r,z,t)=\frac{Q_1}{4\pi T_1}\frac{2}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\sin\frac{n\pi z}{b'_1}\cdot\int_0^\infty\left[1-e^{-n^2\pi^2\overline{t}_{D_1}}+\frac{e^{-n^2\pi^2\overline{t}_{D_1}}-e^{-y^2\overline{t}_{D_1}}}{1-y^2/(n^2\pi^2)}\right]\cdot\left\{\left[\frac{2(r/B_{21})^2(-1)^n y}{F(y)\sin y}-G(y)-1\right]J_0\left[\psi_1(y)\right]-\left[\frac{2(r/B_{21})^2(-1)^n y}{F(y)\sin y}-G(y)+1\right]\cdot J_0\left[\psi_2(y)\right]\frac{dy}{y}\right\} \tag{6}$$

And that in the unpumped aquifer is:

$$s_2(r,t)=\frac{Q_1}{4\pi T_1}\int_0^\infty\left(1-e^{-y^2\overline{t}_{D_1}}\right)\frac{2(r/B_{21})^2}{F(y)}\cdot\left\{J_0\left[\psi_1(y)\right]-J_0\left[\psi_2(y)\right]\right\}\frac{dy}{\sin y} \tag{7}$$

where $J_0\left[\psi_1(y)\right]$ must be set to zero when $\psi_1^2(y)<0$, and $J_0\left[\psi_2(y)\right]$ must be set to zero when $\psi_2^2(y)<0$.

The total compaction from several soil layers can be written as (Gambolati andFreeze, 1973):

$$W_{total}=\sum_{i=1}^{m}W_i(t)=\sum_{i=1}^{m}S_{s_i}\Delta s_i(t)b_i \tag{8}$$

The effect of groundwater users on the cumulative compaction of aquifer 2 was investigated. TWC pumps groundwater from both aquifers 2 and 3 and TYIA pumps groundwater only from aquifer 2. With the assumption that TWC and TYIA are the only users in the Yuanchang area, Figure 7 shows that for the area far from the TWC well field, the compaction can be attributed to TYIA pumping. It covers more than half of the total area. The maximum compaction is 0.2 cm for the period of 2009/12/3-2010/5/6. Figure 8 shows that in the area close to the TWC well field, compaction is significant. Although the influence area of compaction is smaller, the compaction is more significant, reaching a maximum value of 1.25 cm.

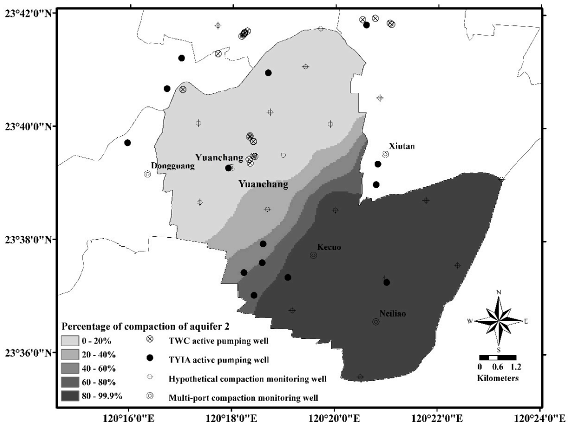

Fig. 7. Percentage of cumulative compaction of aquifer 2 due to single-layer pumping for period of 2009/12/3-2010/5/6.

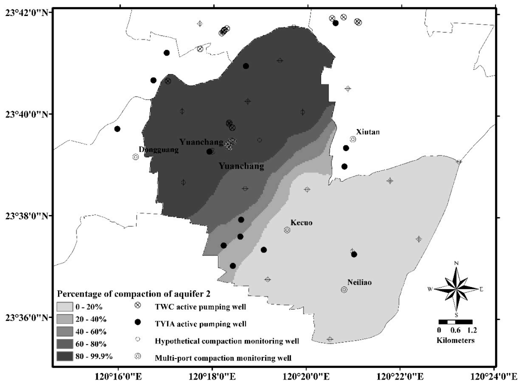

Fig. 8. Percentage of cumulative compaction of aquifer 2 due to multi-layer pumping for period of 2009/12/3-2010/5/6.

CONCLUSION

Summing up, it should be noted that according to the calculations arising now extreme hydrological events are not exclusive. During the period of long-term observations, there are cases of deeper water shortages. In the case of frigid zone, all the rivers of the European part of Russia is characterized by a reduction of scarce periods. For the Volga and the Don River basin real deficits in general no longer occur since 1975-77 years mostly. If we talk about the extremely high water periods, for the Northern Rivers and the basin of the Kama frequency and severity of such events increases, while for the south and center of the region, by contrast, is reduced. In the case of extreme hydrogeological events, both single-layer and multiple-layer users contributes the subsidence. The single-layer groundwater users are responsible for the large-area compaction and that significant local compaction can be attributed to multi-layer users. Constraining multi-layer pumping activities and reducing the amount of groundwater exploitation are required to mitigate the subsidence in Taiwan.

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