Technical Report
Environmental
Monitoring Group

Christchurch – West Melton Groundwater Investigation

Simulation of alternative groundwater abstraction scenarios and their effect on baseflows of the Avon and Heathcote Rivers

Report No. U00/33

Environment Canterbury
Your regional council

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June 2000
(Revised May 2001)

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Executive Summary

The work described in this report was undertaken to provide background for the Christchurch - West Melton Issues and Options paper and provides estimates of the increasing risk of low flows that can be expected as groundwater abstraction increases. In addition the report records the results of a range of analyses done in support of the Issues and Option paper.

The baseflows of the Avon and Heathcote Rivers are maintained by inflows from the Christchurch - West Melton groundwater system. These inflows are dependent on groundwater levels that are affected by seasonal recharge patterns and, to a lesser extent, by abstractions from wells. The effect of groundwater abstractions on the reliability of baseflows in the two rivers is assessed by simulating a range of groundwater abstraction scenarios together with recharge estimates for a 35-year period.

These simulation studies lead to the following general conclusions:

- groundwater abstractions and the river baseflows are derived from the same source: increasing abstractions will result in a reduction of discharge to the spring-fed streams,
- groundwater levels and spring flows vary naturally, largely in response to variable climatic factors. Nevertheless, increased abstraction will increase that variability with the result that low flows will occur more frequently,
- in most years winter recharge is generally sufficient to restore groundwater levels affected by the summer demand for water. However, if abstraction patterns rates are increased there will be an increased risk of unacceptable environmental effects.

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1 Introduction

This report describes the results of computer simulations of the response of the Christchurch - West Melton groundwater system to growing abstraction rates under a range of climatic conditions. The work was undertaken to provide background information for the issues and options document relating to the management of Christchurch water and largely focuses on the relationship between groundwater abstraction and the reliability of baseflows of the Avon and Heathcote Rivers.

Once desired minimum flows have been established for the Avon and Heathcote Rivers more detailed simulations will be undertaken to test alternative management regimes as part of the Section 32 analysis required for the development of a draft plan.

The Christchurch - West Melton groundwater model has been developed to provide a sound basis for the development of water management strategies. The main focus has been on the effects of groundwater abstraction on the baseflows of Christchurch's spring-fed streams. However, the model is also allowing consideration of a range of issues including:

- The controls required to protect against salt-water contamination,
- The effectiveness of alternative groundwater augmentation mechanisms, and
- The appropriateness of different approaches to the imposition of restrictions.

Additional analyses have been undertaken to consider a range of related groundwater management issues considered in the Issues and Options paper including:

- stream depletion due to hydraulically connected wells (Appendix 2)
- consideration of the potential for saltwater intrusion (Appendix 3)

An overview of the groundwater system and the related groundwater management issues was prepared for a series of public consultation meetings. The contents of that presentation are attached in Appendix 4. Appendix 5 provides a comparison of results described in this report with previous assessments of safe yield.

2 Background

Long-term records of groundwater levels in the Christchurch - West Melton area show that as groundwater abstraction has increased the range of levels has increased but that winter recharge is normally sufficient to recharge the system prior to each summer. It is the occasional dry (low recharge) winter that is likely to result in subsequent low flows. As dependence on groundwater increases the consequences of these extremes will be intensified.

The behaviour of the Christchurch - West Melton groundwater system has been represented in a three-dimensional numerical model that has previously been used to examine the consequences of alternative scenarios of growth in groundwater abstraction (Scott, 1996). The same model was later used to consider the effectiveness of springflow protection zones (Woodward Clyde, 1997) and groundwater augmentation through artificial recharge (Little and Scott, 1999). The model is currently being reviewed in light of updated groundwater abstraction and streamflow records.

The preparation of an Issues and Options discussion paper on the management of Christchurch water resources has required information about the relationship between groundwater abstraction and flows in the Avon and Heathcote Rivers. The earlier model simulations explored this relationship by simulating groundwater system response over a 35-year period based on alternative scenarios of groundwater abstraction growth and three possible future climate patterns. That approach illustrated the dominant role that climatic variability has on groundwater levels and consequent springflows. However, though that work indicated the potential for unacceptably large pressure drops within some parts of the confined aquifer, no attempt was made to identify a sustainable limit for groundwater exploitation.

The simulations described in this report examine how baseflow conditions are affected for a range of different abstraction regimes. Rather than attempt to simulate alternative future water use and climate scenarios the approach taken involved a range of fixed levels of demand coupled with the climate pattern recorded between 1964 and 1999. Analysis of the results of a range of simulations provides a description of the way in which the risk of a specified minimum flow changes as abstraction increases.

3 Description of model

3.1 *Model structure*

The simulations described in this report have been carried using a three-dimensional groundwater flow model of an area extending from Halkett in the west to Pegasus Bay in the east (Scott, 2000). The model is essentially the same as the one described in an earlier status report (Scott 1996) and is based on the conceptual model outlined by Talbot et al. (1986). The USGS MODFLOW model (McDonald and Harbaugh, 1988) has been used to represent a multi-layered aquifer over the area illustrated in Figure 1. The model has been set up to encompass a total area of 1,150 km^2 using a variable sized grid with cell dimensions ranging from 0.5 km to 8 km. The row direction of the grid is oriented along 80° E in order to approximately match the average groundwater flow direction within the modelled domain.

No-flow boundaries have been specified for the northern margin of the model on the basis of the assumption that there is insignificant lateral inflow into the system from beyond the Waimakariri River. Similarly the influence of rainfall recharge inland of the western model boundary has been ignored by specifying inactive cells in the south-west corner of the model and applying the default no-flow boundary beyond them. Banks Peninsula has been assumed to be relatively impermeable and has been represented by specifying inactive cells. Some groundwater flow beyond the western flanks of Banks Peninsula has been allowed for by assigning head-dependent boundary conditions to selected cells (shown by ▲) along the southern margin of the model. Heads and conductances for those cells have been chosen to allow for lateral outflow towards Lake Ellesmere.

The offshore coastal boundary has been represented with fixed heads for the uppermost layer of the model only (shown by ◆). This representation of the groundwater flow system is based on the interpretation that only the uppermost confined aquifer is directly connected to the sea and that natural discharge from deeper aquifers is only possible via upward leakage through the sequence of confining layers.

A description of the three-dimensional structure of the aquifer system has been developed from an analysis of borehole logs. Each of the five aquifers in the system has been represented by a single model layer. Within the confined aquifer area the vertical leakance between model layers has been determined from the inferred aquitard thickness. The five layers are continued beyond the confined aquifer area with vertical leakance calculated on the basis that the aquitard has zero thickness. The resulting distribution of vertical leakance between the five layers is illustrated in Figure 2.

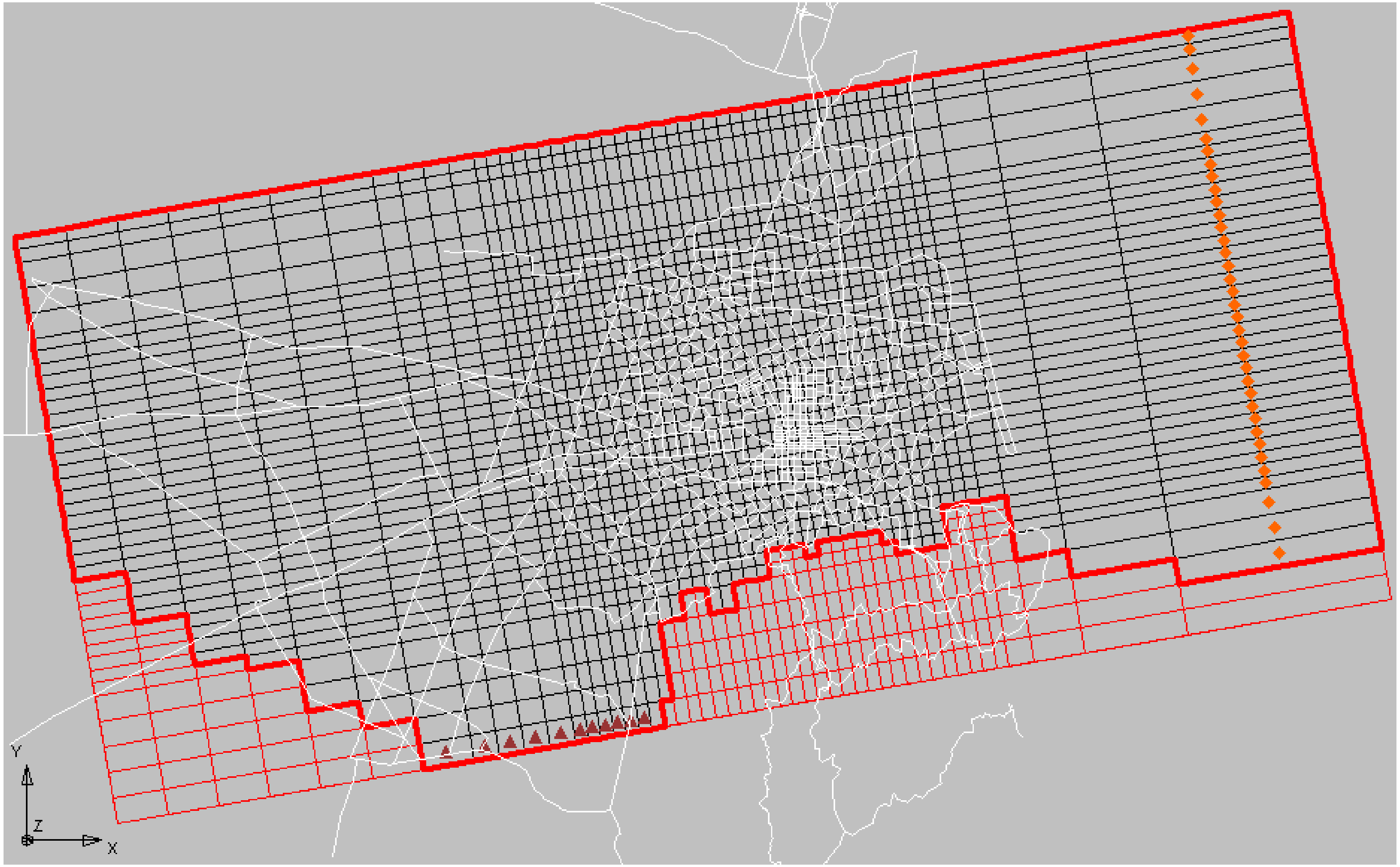

Figure 1: Extent and boundary conditions of the Christchurch - West Melton groundwater model.

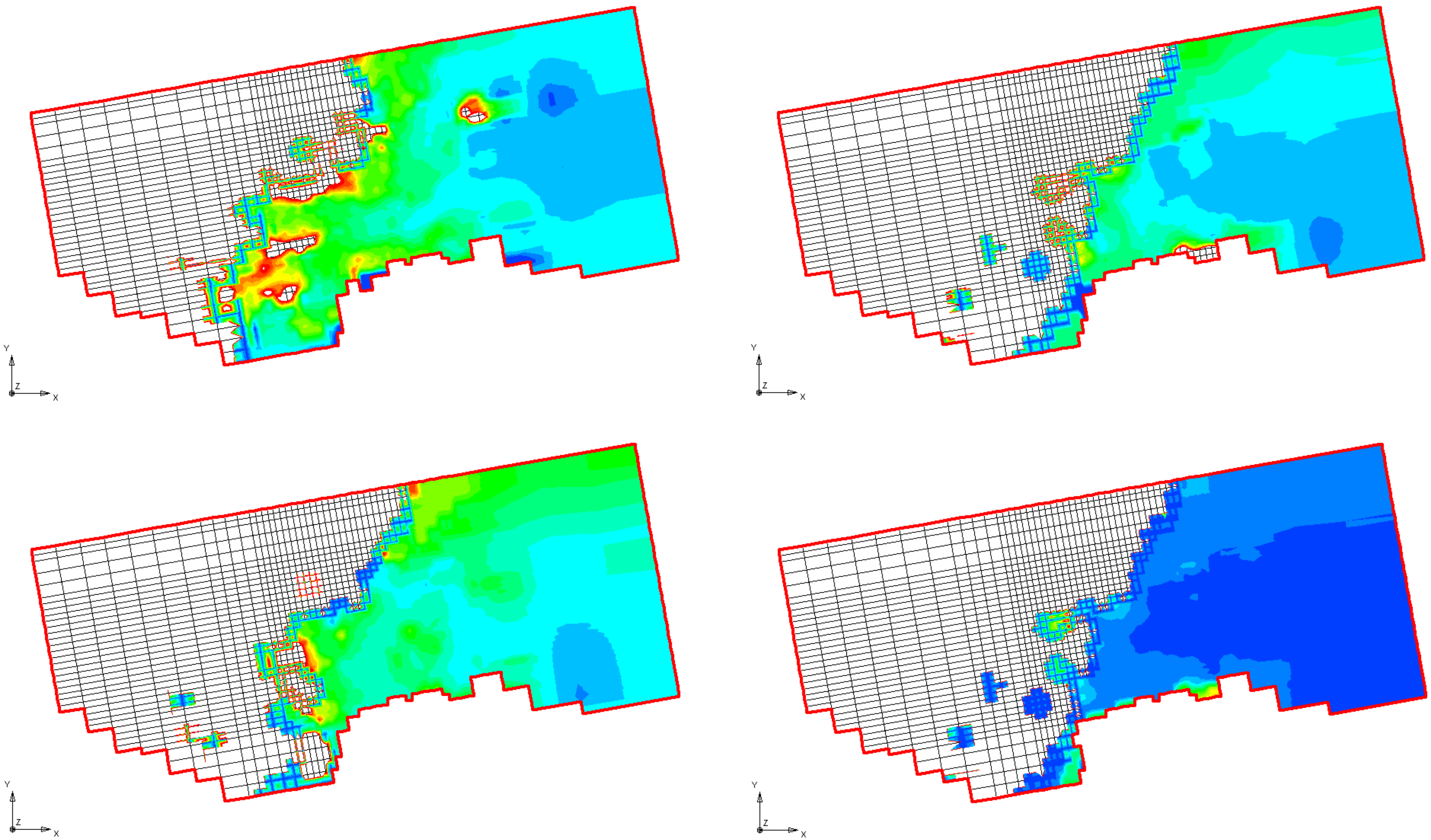

Figure 2: **Distribution of vertical leakance between model layers: layer 1 to 2 - upper-left, layer 2 to 3 – lower left, layer 3 to 4 – upper right, layer 4 to 5 – lower right.**

3.2 *Water balance components*

3.2.1 Inputs

Inflows to the groundwater system from the Waimakariri River are represented by a series of river cells (shown by ■ in Figure 3). In the current version of the model, river level and bed elevations have been set at levels above adjacent groundwater levels so that the river loss is dependent only on the river level. Recharge from the river has been specified as time varying with river levels based on average monthly Waimakariri River. Bed elevations and conductances have been set to ensure that the simulated long-term average recharge is 7.5 m^3/s.

The relatively steady contribution provided by water race return flows is represented by a series of 7 recharge wells (shown by ◆ in Figure 3) with a combined discharge of 0.7 m3/s.

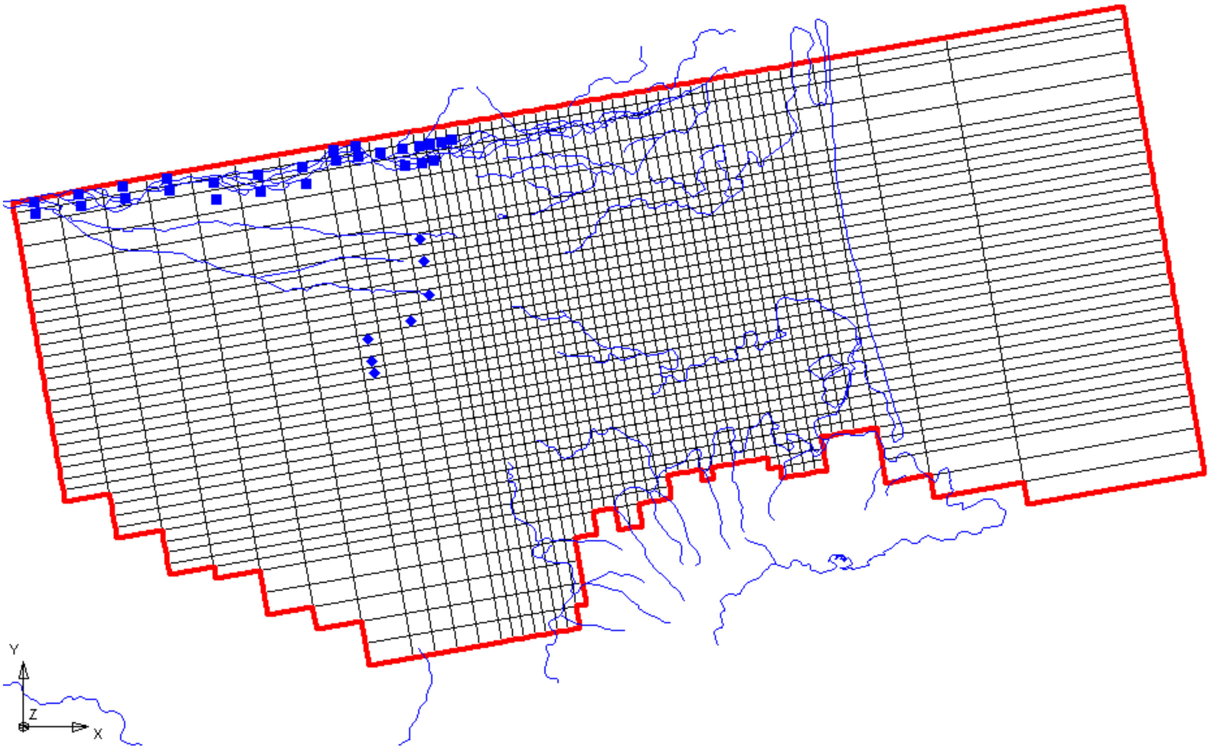

Figure 3: Location of model river cells (■) and recharge wells (◆) shown in relation to surface water features.

Rainfall recharge is assigned to the uppermost layer of the unconfined zone of the groundwater system (Figure 4). Together with the inactive cells in the southwest corner of the model this approach roughly demarcates a triangular zone to the west of Christchurch within which rainfall recharge predominantly flows towards the city. The temporal pattern of rainfall recharge has been assessed by calculating daily drainage through unsaturated soil using a simple soil moisture model (Thorpe & Scott, 1999). The daily drainage terms have been accumulated to monthly totals to provide the recharge input for the groundwater model.

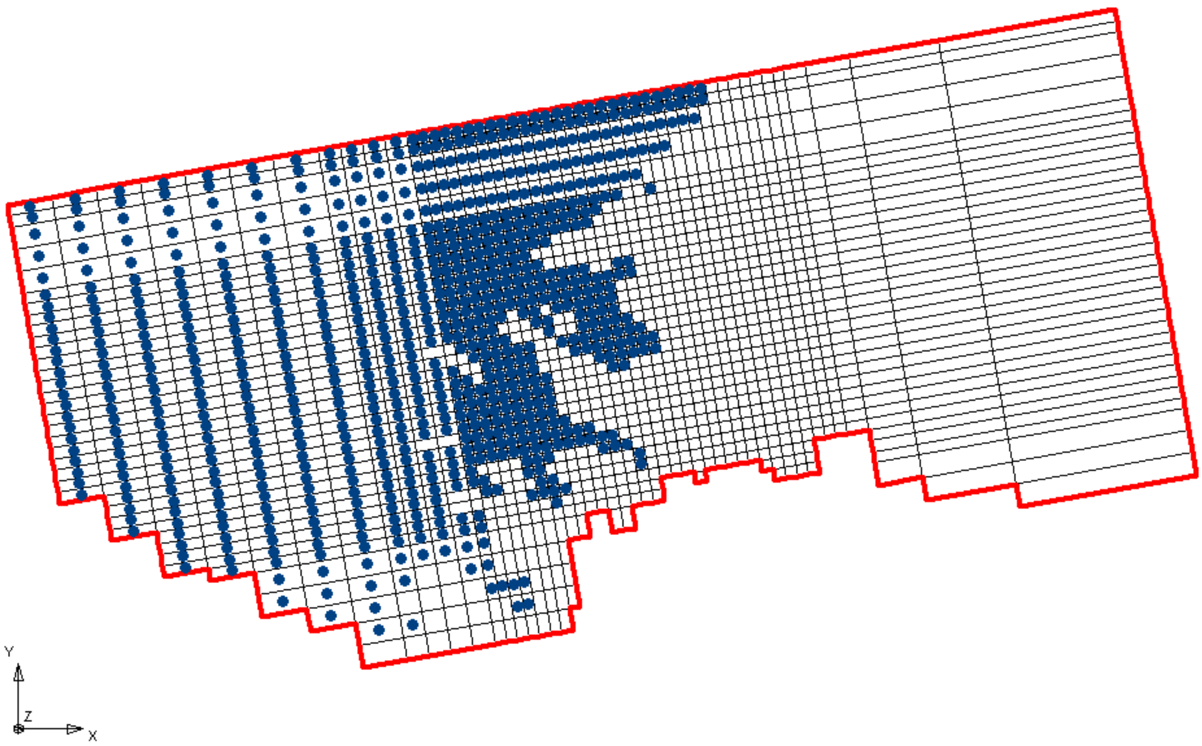

Figure 4: Configuration of rainfall recharge area over unconfined aquifer of the model.

3.2.2 Outputs

3.2.2.1 Spring flows

Groundwater discharge to the South Branch, Styx River, Avon River, Heathcote River, Halswell River and LII drain is allowed for by a series of 98 drain cells (Figure 5). Elevation and conductance terms assigned to those cells are designed to represent the behaviour the springs in each of those catchments.

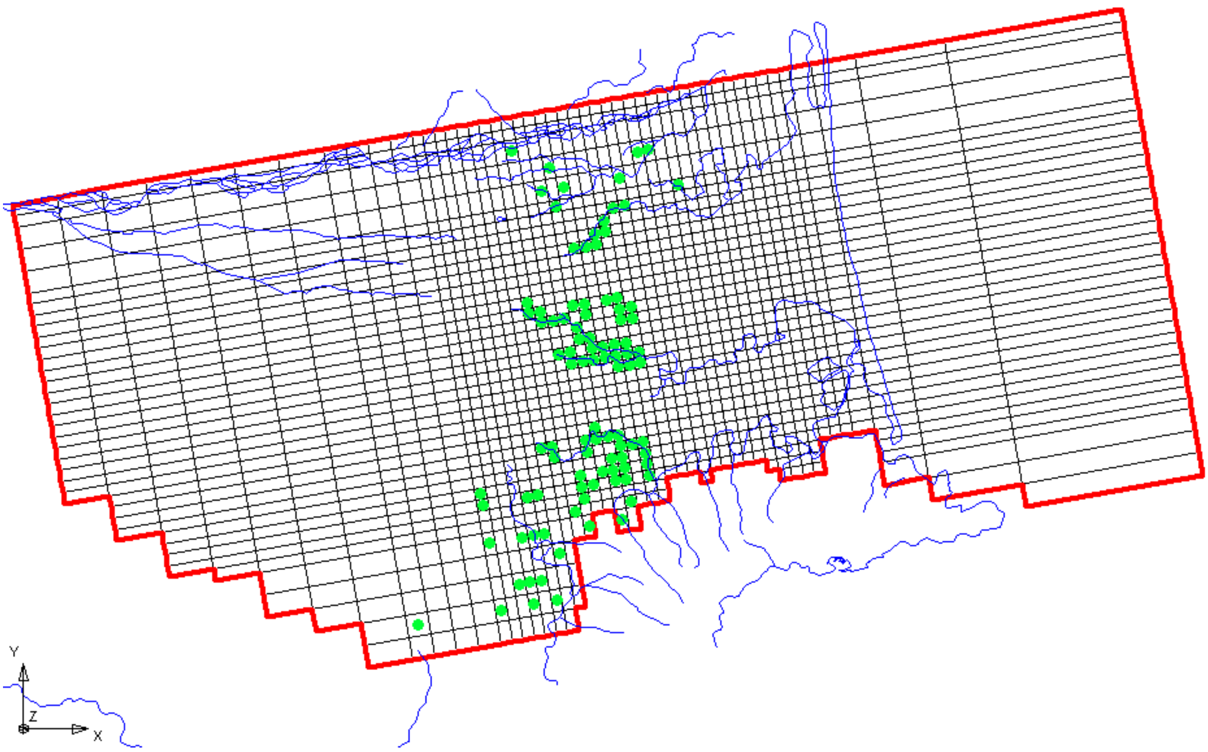

Figure 5: Configuration of drain cells representing groundwater inflow.

3.2.2.2 Wells

Groundwater abstractions from wells are accounted for by the specification of a large number of well cells. In its present state of development the model incorporates 621 wells assigned to the appropriate model layer as determined from well depth. The location of wells in each of the model layers is illustrated in Figure 6. The temporal pattern of groundwater abstraction has been derived from records of measured discharge (in the case of municipal supplies and some industrial users) or calculated on the basis of consent parameters and/or soil moisture model based estimates of irrigation demand. A summary of the overall estimated water use record for the model area is provided in Appendix 1

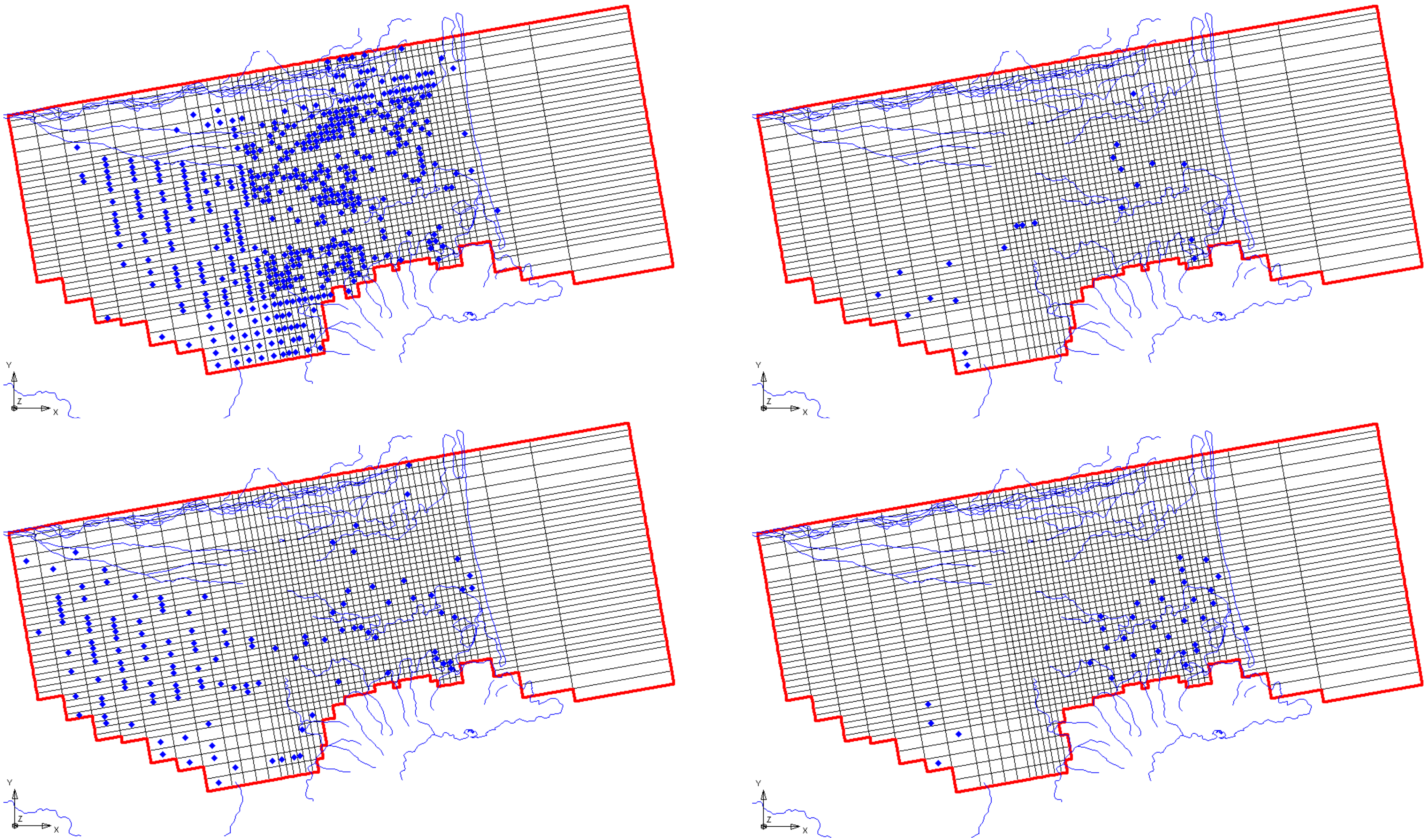

Figure 6: Distribution of well cells: layer 1 - upper-left, layer 2 – lower left, layer 3 – upper right, layer 4 – lower right, layer 5 – not shown (8 well cells only).

3.3 *Model adjustment in response to updated water balance*

The model structure and water balance components described above are directly based on the version of the model developed using water balance components estimated for the period 1965 to 1995 (Scott, 1996). Prior to this new set of simulations the records of groundwater abstraction were updated to the end of June 1999 and the model assessed on the basis of how well it reproduced Avon River and Heathcote River flows over the extended period. That assessment showed that the model simulated baseflows that were above the lowest recorded in those four years and, as a result, alternative descriptions of river and rainfall recharge were evaluated in an effort to improve the model performance. The alternatives considered were:

Case 1: Waimakariri River recharge a function of mean monthly discharge with an average rate of 7.5 m^3/s; rainfall recharge based on an average soil available water holding capacity of 62.5 mm, including allowance for application of irrigation.

Case 2: Waimakariri River recharge constant at 7.5 m^3/s; rainfall recharge based on an average soil available water holding capacity of 62.5 mm, including allowance for application of irrigation.

Case 3: Waimakariri River recharge a function of mean monthly discharge with an average rate of 7.5 m^3/s; rainfall recharge based on an average soil available water holding capacity of 100 mm, no allowance for effects of irrigation.

Case 4: Waimakariri River recharge constant at 7.5 m^3/s; rainfall recharge based on an average soil available water holding capacity of 100 mm, no allowance for effects of irrigation.

This comparison showed that Case 2 provided a significantly better representation of low baseflows over the 1995 to 1999 period suggesting that the variability of Waimakariri River recharge had been over-estimated in the previous use of the model. Accordingly the model recharge inputs for the current set of simulations were specified using the relationships adopted for Case 2.

The rainfall recharge estimate adopted for the simulations is illustrated in Figure 7 along with the total rainfall from which it is derived (Christchurch Airport). For the 35-year period the average proportion of annual rainfall estimated to form recharge was 35% but ranged from 10% (in 1969 and 1982) and 53% (in 1974 and 1978).

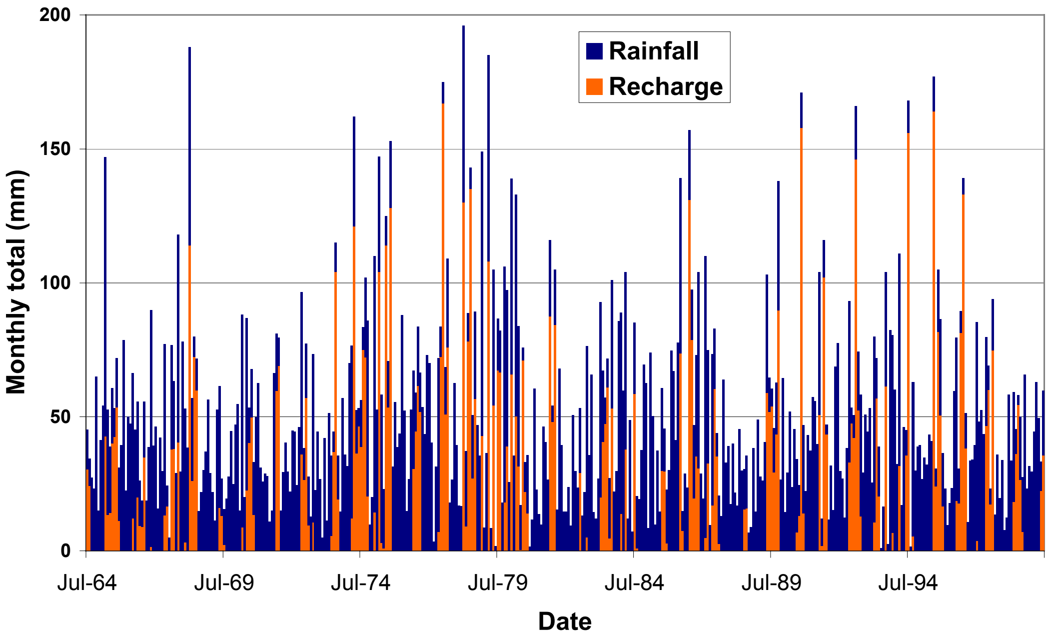

Figure 7: Recorded monthly rainfall and simulated monthly rainfall recharge adopted for the 35-year simulation period.

4 Simulation of alternative groundwater abstraction scenarios

4.1 *Description of scenarios*

The objective of this series of simulations was to examine the effects of varying levels of groundwater abstraction on the reliability of baseflows of the Avon and Heathcote Rivers. Groundwater abstraction varies in response to many different factors but in simple terms the historic pattern of abstraction can be seen as the response to a climatically governed seasonal demand superimposed on a growing capacity to take and use groundwater. However, since both the rate of demand growth and the nature of future climate are both unknown, forecasting future groundwater abstraction is highly speculative.

It is possible to simplify the analysis of alternative abstraction regimes by reposing the problem as one involving hindcasting. In the simulations reported in this section the question has been posed "what would baseflows have been over the period 1964 to 1999 if groundwater abstraction had been x% of that occurring in 1998/99?" This has been done by carrying out the following steps:

- treating the spatial and temporal pattern of abstraction for the 1998/99 year as a base case,
- defining alternative groundwater abstraction scenarios as specified percentages of that base case, and
- simulating groundwater levels and spring-fed stream flows using the climate based estimates of rainfall recharge for the 35-year period from 1964 to 1999.

This approach is somewhat artificial since it ignores the effect that climatic factors have on the demand for water. Nevertheless, this simplification makes it possible to illustrate how different abstraction rates affect baseflow reliability and to consider a range of different approaches to exploiting additional quantities of groundwater.

There are a number of obvious limitations to this approach:

- though the 35 years of actual climate history provides a sample of the natural variability, a more severe pattern could occur even without the additional complication of climate change,
- the approach doesn't allow for potential benefits from varying the spatial pattern of abstractions (e.g. as might be established by the declaration of springflow protection zones),
- the link between climate and demand is neglected.

Despite these limitations the results do provide a comparative indication of the possible effects of different levels of abstraction.

4.1.1 Case 1 – Across the board change

For this case the 1998/99 water use pattern was used to define higher (or lower) levels of abstraction on a strictly pro-rata basis. A specified adjustment factor was applied to every abstraction term in the Modflow well package input for the 1998/99 period and written to a new well package input to represent 35 years with a repeated annual cycle. Fourteen abstraction scenarios were evaluated ranging from 70% (i.e. 30% reduction) to 200% (i.e. 100% increase) of the 1998/99 abstraction.

4.1.2 Case 2 – Layer 1 fixed

This case was designed to represent the outcome of a policy to limit future abstractions from the shallowest aquifer. For all simulations the abstractions from Layer 1 of the model were fixed to match those for the 1998/99 year. Ten alternative abstraction scenarios were evaluated with total abstraction ranging from 110% to 200% of the 1998/99 abstraction with the adjustment factor applied so that increases in abstraction were met by changes in abstraction from the lower model layers only. The option of fixing Layer 1 abstractions would not be irrelevant for scenarios involving a reduction in total abstraction. Accordingly Case 2 was limited to scenarios with increased total abstraction.

4.1.3 Case 3 – Unconfined/confined restriction regimes

This case was included to illustrate the comparative effectiveness of restrictions on abstractions from the unconfined and confined. Abstraction rates were based on 130% of the 1998/99 abstraction but alternative restrictions were evaluated for the following scenarios:

(a) No controls
(b) No pumping from within confined aquifer zone when total drain discharge falls to 700,000 m^3/d
(c) No pumping from within confined aquifer zone when total drain discharge falls to 413,835 m^3/d
(d) No pumping from within unconfined aquifer zone when total drain discharge falls to 700,000 m^3/d
(e) No pumping from within unconfined aquifer zone when total drain discharge falls to 413,835 m^3/d

4.2 *Results*

4.2.1 Case 1 – Across the board change

Each of the fourteen simulation runs has been used to provide estimates of Avon River and Heathcote River baseflows (as mean monthly flow) for the 35-year simulation period. Typical results are illustrated in Figure 8 with simulated Avon River baseflow for three scenarios: abstraction set to 70% (upper line), 100% (middle line) and 130% (lower line) of the 1998/99 rate. For the first of these scenarios (70%) it can be seen that the baseflow drops below the 1500 l/s level for 5 of the 35 years (1970, 1971, 1972, 1973 and 1989). In contrast, for the last of these scenarios (130%) the baseflow drops below 1500 l/s for every year except 1980.

The baseflow distribution and its sensitivity to abstraction rate are shown in Figure 9 for the 100%, 130% and 200% scenarios. The effect of increasing abstraction on the flow is clearly illustrated by considering the flow exceeded 90% of the time which falls from 1330 l/s (100%) to 610 l/s (200%).

Results of all fourteen scenarios are summarised in Table 1 (Avon River) and Table 2 (Heathcote River) in terms of annual series of monthly minima.

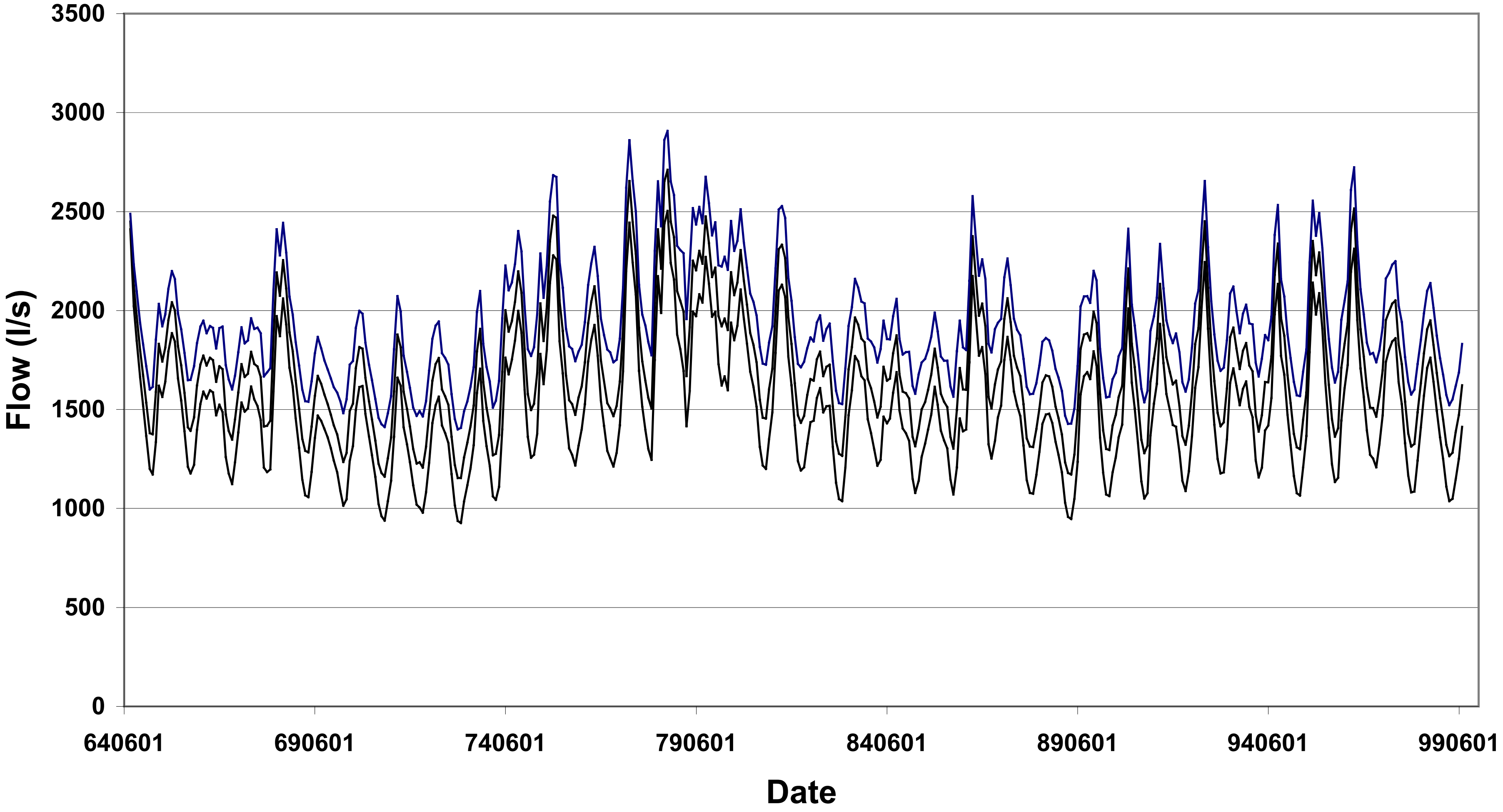

Figure 8: Simulated Avon River baseflow for groundwater abstractions of 70%, 100% and 130% of the 1998/99 rate.

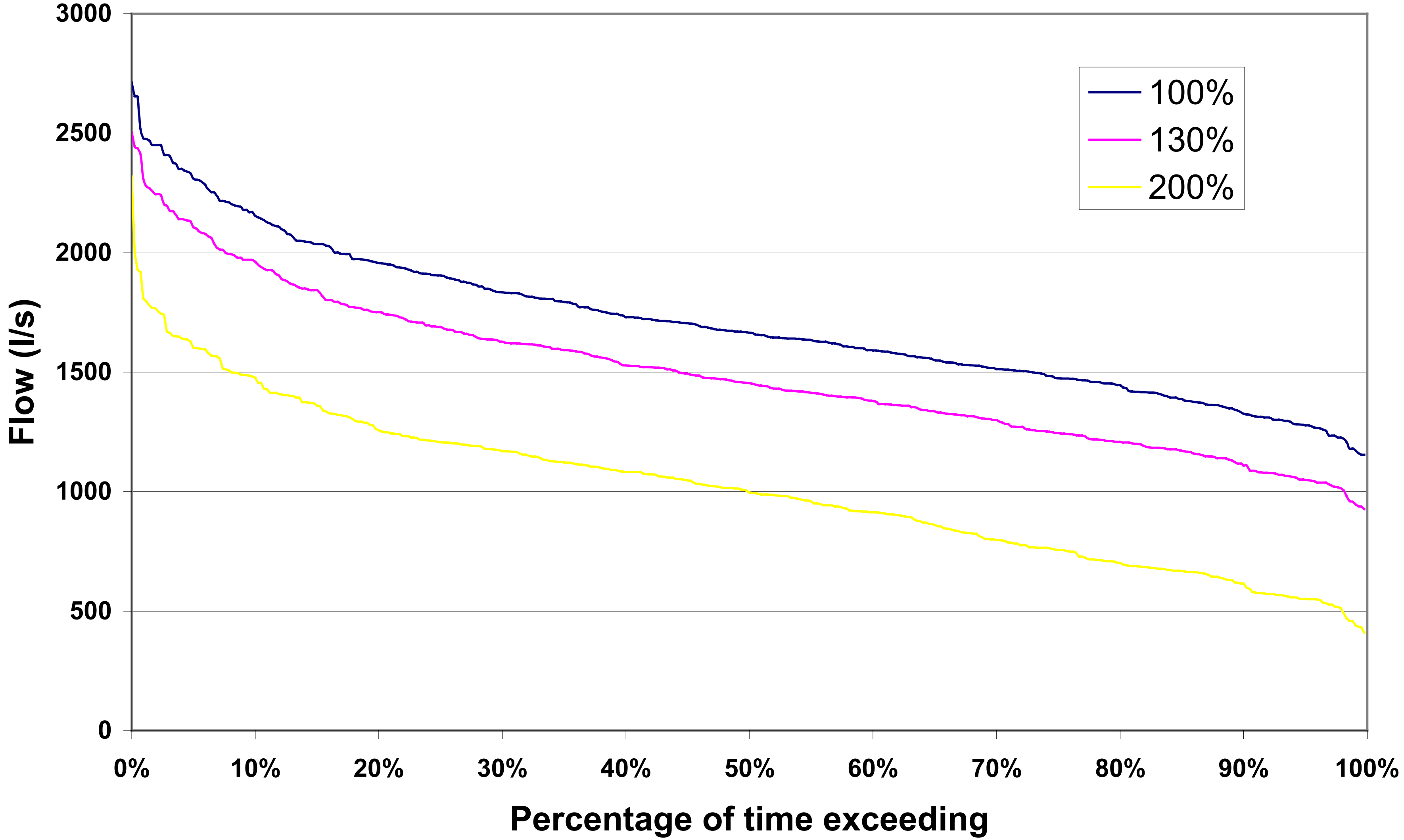

Figure 9: Distribution of simulated Avon River baseflow for groundwater abstractions of 100%, 130% and 200% of 1998/99 rate.

Year	Change of abstraction rate relative to 1998/99													
	-30%	**-20%**	**-10%**	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
1965	1553	1473	1389	1313	1238	1167	1094	1020	947	877	808	737	664	591
1966	1596	1503	1411	1330	1252	1176	1100	1023	946	873	799	724	645	576
1967	1553	1463	1369	1287	1207	1129	1047	976	901	824	744	667	598	529
1968	1616	1525	1435	1351	1268	1187	1107	1025	949	870	791	710	628	558
1969	1492	1396	1307	1224	1141	1059	983	906	825	741	667	594	525	451
1970	1433	1340	1256	1175	1092	1017	938	861	777	692	621	551	478	399
1971	1365	1269	1185	1102	1025	944	865	780	706	630	558	482	403	330
1972	1419	1327	1233	1145	1067	984	904	819	737	660	585	509	424	348
1973	1349	1261	1177	1093	1016	934	853	769	693	617	543	462	382	307
1974	1463	1374	1291	1215	1130	1045	965	881	795	709	631	555	477	406
1975	1720	1619	1524	1432	1346	1265	1186	1108	1019	938	852	768	679	597
1976	1698	1600	1504	1404	1311	1227	1144	1059	974	895	811	725	641	568
1977	1692	1595	1497	1397	1306	1221	1138	1052	971	890	805	717	637	563
1978	1728	1630	1534	1434	1343	1253	1171	1087	1001	920	838	754	665	592
1979	1904	1795	1695	1600	1510	1426	1339	1252	1165	1085	1005	922	835	758
1980	2159	2054	1942	1828	1715	1606	1517	1427	1329	1231	1146	1059	962	872
1981	1679	1581	1483	1385	1292	1209	1125	1040	957	877	794	709	629	555
1982	1660	1560	1460	1369	1280	1197	1114	1031	945	866	785	703	617	546
1983	1481	1384	1292	1207	1122	1041	962	883	799	716	641	569	492	417
1984	1686	1584	1487	1393	1307	1222	1141	1057	973	895	813	728	641	566
1985	1528	1428	1339	1251	1169	1085	1004	926	845	762	674	602	528	460
1986	1514	1417	1327	1239	1158	1071	993	913	831	746	661	586	514	445
1987	1737	1632	1533	1438	1347	1260	1175	1094	1008	924	843	762	676	592
1988	1526	1427	1336	1250	1164	1079	1000	921	837	751	673	597	525	445
1989	1377	1285	1199	1113	1035	953	873	787	709	632	559	482	400	325
1990	1511	1412	1323	1237	1152	1067	988	908	823	736	661	586	510	432
1991	1487	1387	1303	1220	1138	1054	976	899	818	735	651	581	512	431
1992	1542	1447	1349	1263	1179	1096	1015	937	856	772	689	615	542	466
1993	1643	1542	1443	1352	1266	1183	1100	1015	933	853	771	685	604	533
1994	1614	1514	1416	1328	1244	1163	1080	996	918	838	756	670	592	524
1995	1520	1421	1326	1240	1155	1069	990	911	828	742	664	590	516	438
1996	1585	1486	1392	1301	1220	1139	1057	974	895	817	735	650	575	506
1997	1692	1591	1495	1393	1302	1218	1133	1046	964	883	798	710	631	556
1998	1526	1427	1335	1251	1171	1088	1006	928	848	762	682	605	532	454
1999	1471	1375	1289	1205	1122	1037	962	883	801	717	638	566	491	414
Min	1349	1261	1177	1093	1016	934	853	769	693	617	543	462	382	307
Median	1553	1463	1369	1287	1207	1129	1047	974	895	817	735	650	575	506
Max	2159	2054	1942	1828	1715	1606	1517	1427	1329	1231	1146	1059	962	872

Table 1: Annual monthly minima Avon River baseflow (l/s) for alternative across the board changes in abstraction rates.

Year	Change of abstraction rate relative to 1998/99													
	-30%	-20%	-10%	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
1965	716	649	580	512	443	379	308	252	204	166	130	94	58	18
1966	741	670	599	527	454	387	316	255	207	168	130	91	53	12
1967	756	687	616	545	471	400	326	260	212	173	133	94	54	13
1968	749	675	601	527	453	384	313	255	206	165	123	84	43	7
1969	708	632	557	479	407	333	268	214	173	133	92	51	12	0
1970	672	594	517	443	367	301	237	189	150	109	66	21	0	0
1971	637	560	484	410	338	275	214	171	130	89	44	8	0	0
1972	632	555	479	408	343	283	231	183	140	97	54	10	0	0
1973	622	545	469	394	326	263	203	163	120	77	35	3	0	0
1974	669	593	514	441	369	308	242	188	147	104	61	13	0	0
1975	785	710	634	558	481	405	333	277	231	183	145	105	63	20
1976	818	744	669	594	519	441	369	298	240	193	153	110	69	26
1977	810	734	660	585	509	430	357	285	232	184	143	102	59	16
1978	846	777	706	634	560	482	403	329	255	206	166	125	84	43
1979	917	846	776	703	629	555	478	402	323	259	204	166	128	89
1980	972	889	817	744	670	596	520	445	367	305	250	206	160	123
1981	809	733	659	585	507	430	356	275	224	181	142	100	59	18
1982	787	713	637	560	482	405	329	259	207	166	125	84	43	8
1983	703	626	548	471	397	321	259	204	165	123	82	40	7	0
1984	807	731	655	578	501	423	347	272	221	176	135	94	51	10
1985	716	639	562	482	408	331	267	212	168	127	86	43	7	0
1986	706	629	552	473	400	324	260	204	163	122	79	35	3	0
1987	822	748	672	596	519	438	364	283	231	183	143	102	61	16
1988	723	645	568	489	415	339	272	216	173	132	91	48	8	0
1989	639	562	484	410	336	275	212	170	128	86	43	7	0	0
1990	721	644	566	487	413	338	272	216	173	133	91	48	8	0
1991	705	629	550	473	398	323	259	206	165	123	81	38	7	0
1992	754	682	608	530	453	379	301	242	194	155	114	71	28	2
1993	779	705	629	552	473	397	319	254	201	161	120	79	36	5
1994	769	693	616	538	459	387	308	247	196	156	115	74	31	3
1995	723	647	570	492	417	341	273	217	175	133	92	49	10	0
1996	757	683	606	530	451	377	300	240	193	153	112	71	28	3
1997	795	720	645	570	494	417	344	283	234	186	147	104	63	20
1998	726	650	573	494	420	344	275	219	176	137	94	53	12	0
1999	692	614	537	459	385	313	249	196	156	115	72	30	3	0
Min	622	545	469	394	326	263	203	163	120	77	35	3	0	0
Median	741	670	599	527	451	379	301	242	194	155	114	71	28	3
Max	972	889	817	744	670	596	520	445	367	305	250	206	160	123

Table 2: Annual monthly minima Heathcote River baseflow (l/s) for alternative across the board changes in abstraction rates. (NB: Simulated flows have been increased by 65% to adjust simulated minimum mean monthly flows to match the observed low flows over the 1991 - 1999 period).

4.2.2 Case 2 – Layer 1 fixed

Results of the ten scenarios are summarised in Table 3 (Avon River) and Table 4 (Heathcote River) in terms of annual series of monthly minima.

Year	Change of abstraction rate relative to 1998/99										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
1965	1375	1315	1253	1196	1137	1078	1018	957	896	836	779
1966	1393	1328	1263	1200	1138	1074	1010	944	879	818	756
1967	1348	1280	1216	1152	1087	1019	959	896	833	768	701
1968	1414	1344	1274	1206	1139	1069	1000	931	864	796	726
1969	1283	1215	1146	1077	1012	947	882	814	745	674	612
1970	1235	1165	1094	1029	961	892	822	750	676	611	550
1971	1161	1094	1028	959	891	821	748	684	622	560	491
1972	1206	1137	1068	999	929	858	784	714	648	585	515
1973	1154	1085	1018	947	878	805	735	667	605	540	469
1974	1268	1203	1128	1057	986	911	838	762	683	615	548
1975	1498	1417	1345	1275	1207	1138	1070	996	920	846	773
1976	1473	1392	1315	1242	1174	1103	1030	957	889	820	748
1977	1466	1385	1309	1236	1167	1095	1023	952	883	812	739
1978	1504	1422	1346	1270	1201	1132	1060	987	914	846	776
1979	1669	1588	1511	1441	1369	1296	1222	1151	1079	1008	937
1980	1902	1813	1721	1629	1549	1475	1402	1321	1238	1160	1088
1981	1454	1370	1296	1224	1156	1084	1013	940	872	803	732
1982	1433	1356	1283	1211	1141	1069	997	922	851	782	709
1983	1266	1196	1124	1055	987	921	851	779	705	640	577
1984	1460	1378	1309	1236	1166	1094	1021	946	876	804	731
1985	1314	1241	1171	1099	1025	957	886	815	741	665	593
1986	1302	1229	1159	1084	1014	944	872	799	722	646	580
1987	1506	1423	1348	1274	1203	1131	1060	985	909	837	766
1988	1310	1238	1166	1094	1026	958	889	817	745	670	598
1989	1172	1104	1036	966	897	824	750	682	619	556	486
1990	1296	1225	1154	1081	1013	944	875	804	730	659	594
1991	1280	1209	1139	1067	997	929	861	790	716	642	576
1992	1323	1252	1182	1111	1041	974	906	836	764	689	621
1993	1415	1340	1268	1197	1126	1053	979	906	837	766	692
1994	1388	1318	1245	1176	1105	1033	959	890	820	748	673
1995	1299	1228	1157	1085	1016	948	880	809	736	663	598
1996	1363	1292	1222	1154	1082	1011	938	870	802	730	658
1997	1464	1379	1306	1233	1164	1091	1017	946	877	806	732
1998	1313	1242	1173	1102	1031	960	893	824	753	680	606
1999	1265	1194	1124	1051	983	914	844	772	697	624	562
Min	1154	1085	1018	947	878	805	735	667	605	540	469
Median	1348	1280	1216	1152	1082	1011	938	870	802	730	658
Max	1902	1813	1721	1629	1549	1475	1402	1321	1238	1160	1088

Table 3: Annual monthly minima Avon River baseflow (l/s) for alternative abstraction rates with layer 1 fixed at 1998/99 rate.

Year	Change of abstraction rate relative to 1989/99										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
1965	512	474	412	354	301	250	201	166	133	99	66
1966	527	487	420	359	305	252	201	165	130	94	58
1967	545	504	435	364	310	257	204	168	132	94	58
1968	527	484	415	361	305	249	196	158	122	82	44
1969	479	441	369	313	259	201	165	128	91	51	10
1970	443	402	341	283	226	179	140	102	61	20	0
1971	410	372	315	259	199	161	122	82	41	7	0
1972	408	377	323	268	216	171	132	91	49	8	0
1973	394	361	303	245	189	151	112	71	30	2	0
1974	441	400	347	288	229	176	137	97	56	12	0
1975	558	512	438	375	321	268	222	176	142	102	63
1976	594	550	473	402	346	288	231	186	148	109	69
1977	585	538	461	392	336	278	221	176	138	99	59
1978	634	591	515	438	362	305	249	198	161	122	84
1979	703	660	585	510	435	361	301	245	199	163	127
1980	744	700	624	548	473	398	347	296	250	206	161
1981	585	540	461	389	324	268	212	173	137	97	59
1982	560	515	440	366	308	250	196	160	122	82	43
1983	471	430	361	303	247	193	155	117	77	36	5
1984	578	534	456	380	321	265	209	168	130	91	49
1985	482	441	370	311	257	196	158	120	79	38	5
1986	473	433	364	306	249	191	153	114	72	31	2
1987	596	550	471	397	334	278	221	176	138	99	59
1988	489	448	374	315	260	201	163	125	84	44	8
1989	410	372	313	255	198	158	119	77	36	5	0
1990	487	446	372	315	259	201	165	125	86	46	8
1991	473	431	361	303	247	193	155	117	76	35	5
1992	530	484	413	346	290	231	184	147	107	68	26
1993	552	506	431	359	301	244	191	155	115	76	36
1994	538	494	420	351	295	237	188	150	110	71	30
1995	492	450	374	316	260	203	165	127	87	48	8
1996	530	484	412	344	287	229	184	147	107	68	28
1997	570	525	448	382	329	277	222	179	140	102	61
1998	494	453	377	319	263	206	168	128	89	49	10
1999	459	418	352	295	237	186	147	109	68	26	2
Min	394	361	303	245	189	151	112	71	30	2	0
Median	527	484	412	346	290	231	184	147	107	68	28
Max	744	700	624	548	473	398	347	296	250	206	161

Table 4: Annual monthly minima Heathcote River baseflow (l/s) for alternative abstraction rates with layer 1 fixed at 1998/99 rate. (NB: Simulated flows have been increased by 65% to adjust simulated minimum mean monthly flows to match the observed low flows over the 1991 - 1999 period).

4.2.3 Case 3 – Unconfined/confined restriction regimes

Results of the four simulations undertaken to evaluate alternative restriction regimes are illustrated in Figure 10 to show the distribution of simulated baseflow compared to the situation with no controls. In this case, rather than assess a range of abstraction levels a single 30% increase has been adopted and the results illustrate the comparative effectiveness of alternative strategies for applying restrictions.

The 'No Control' curve shows the distribution of baseflow in the absence of any restrictions (equivalent to the 30% increase column of Table 1) and provides a datum against which the other alternatives can be compared.

The two Case B curves indicate the change in distribution if restrictions are applied at comparatively low flows (equivalent to around 1160 l/s in the Avon). The effectiveness of limiting these restrictions to unconfined or confined aquifer abstractions is almost the same and results in an improvement of low flow of around 150 l/s.

The two Case A curves result from much earlier imposition of restrictions (equivalent to around 1960 l/s in the Avon) and in this case there is markedly more achieved by the restriction to confined aquifer abstractions compared to the unconfined.

None of these restriction options are particularly realistic options but have been included to provide results consistent with some of the earlier work described in Little and Scott (1999) where the same flow rates were used as restriction triggers. Nevertheless, the results do once again illustrate the potential for different types of response to restrictions in different aquifer zones and suggest that such options should be studied more closely.

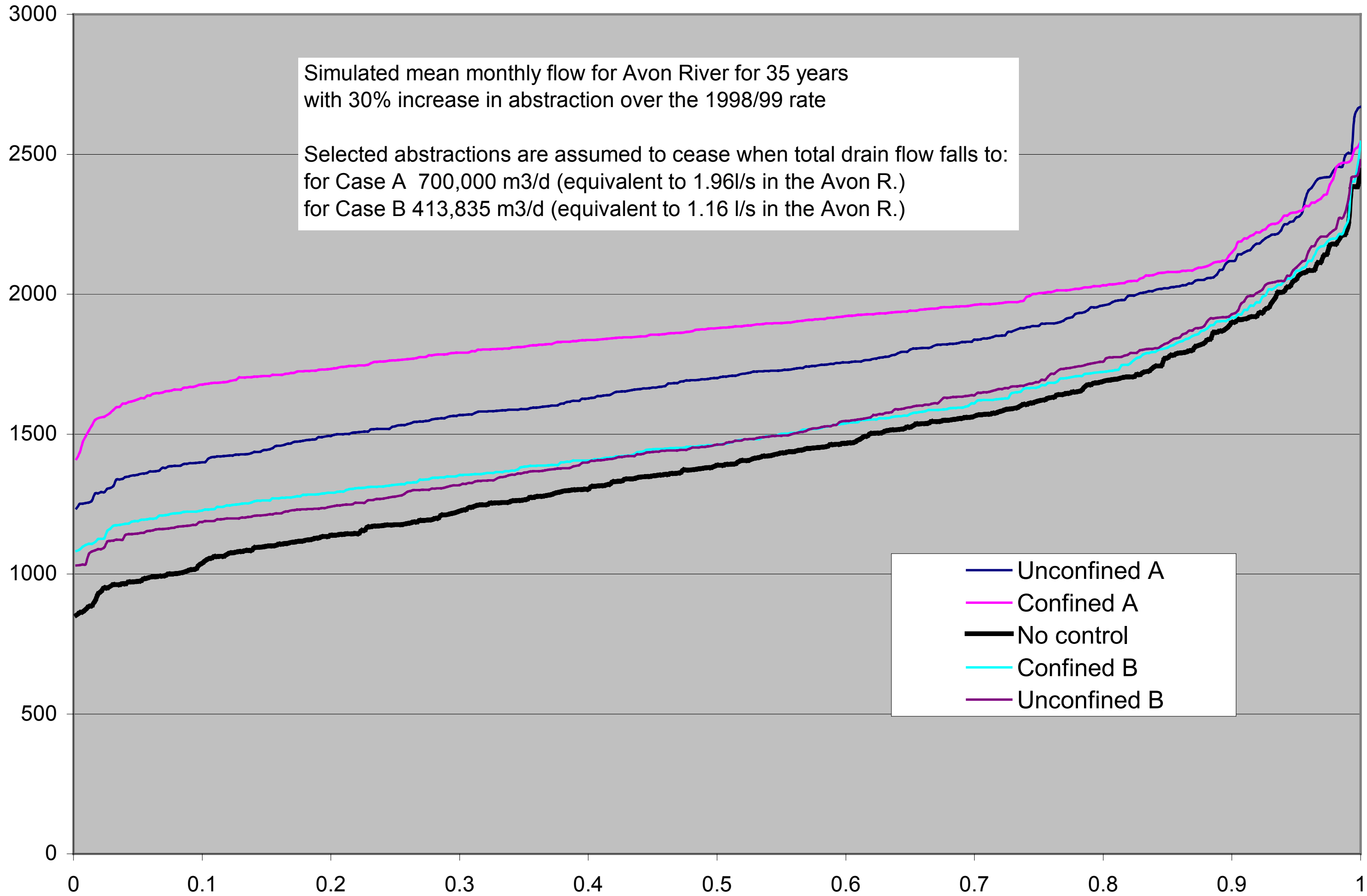

Figure 10: Distribution of simulated Avon River baseflows for alternative restriction regimes.

4.3 *Discussion*

4.3.1 Case 1 - Comparison of across the board changes in abstraction

The simulation results described above can be used to provide a description of the way in which low flow reliability changes with different levels of groundwater abstraction. This has been done by considering the percentage of years in the simulation period where the minimum flow fell below some specified value. For example, Table 1 shows for 0% change of abstraction rate the minimum flow would have fallen below 1200 l/s in 5 years of the 35-year simulation period. In that case the probability of a minimum flow of 1200 l/s can be expressed as 5 in 35 or 14%. Equivalent probabilities for all the abstraction rates considered and for a range of threshold flows are presented in Table 5 for the Avon River and Table 6 for the Heathcote River.

Flow (l/s)	Change of abstraction rate relative to 1989/99													
	-30%	-20%	-10%	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
1400	9%	29%	57%	83%	94%	94%	97%	97%	100%	100%	100%	100%	100%	100%
1300	0%	9%	23%	51%	74%	94%	94%	97%	97%	100%	100%	100%	100%	100%
1200	0%	0%	9%	14%	49%	71%	94%	94%	97%	97%	100%	100%	100%	100%
1100	0%	0%	0%	3%	14%	49%	60%	91%	94%	97%	97%	100%	100%	100%
1000	0%	0%	0%	0%	0%	11%	37%	57%	86%	94%	94%	97%	100%	100%
900	0%	0%	0%	0%	0%	0%	9%	26%	51%	86%	94%	94%	97%	100%
800	0%	0%	0%	0%	0%	0%	0%	9%	20%	49%	74%	94%	94%	97%
700	0%	0%	0%	0%	0%	0%	0%	0%	3%	14%	49%	60%	94%	94%
600	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	11%	40%	57%	94%

Table 5: Percentage of years with Avon River minimum flow below specified threshold. Shaded areas show circumstances where the specified flow is always (or never) reached.

Flow (l/s)	Change of abstraction rate relative to 1989/99													
	-30%	-20%	-10%	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
700	20%	66%	91%	94%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
650	11%	46%	77%	94%	97%	100%	100%	100%	100%	100%	100%	100%	100%	100%
600	0%	17%	51%	91%	94%	100%	100%	100%	100%	100%	100%	100%	100%	100%
550	0%	3%	23%	66%	91%	94%	100%	100%	100%	100%	100%	100%	100%	100%
500	0%	0%	11%	46%	77%	94%	97%	100%	100%	100%	100%	100%	100%	100%
450	0%	0%	0%	17%	49%	91%	94%	100%	100%	100%	100%	100%	100%	100%
400	0%	0%	0%	3%	26%	66%	91%	94%	100%	100%	100%	100%	100%	100%
350	0%	0%	0%	0%	11%	46%	80%	94%	97%	100%	100%	100%	100%	100%
300	0%	0%	0%	0%	0%	11%	46%	91%	94%	97%	100%	100%	100%	100%
250	0%	0%	0%	0%	0%	0%	20%	54%	91%	94%	97%	100%	100%	100%
200	0%	0%	0%	0%	0%	0%	0%	20%	54%	91%	94%	97%	100%	100%
150	0%	0%	0%	0%	0%	0%	0%	0%	14%	46%	89%	94%	97%	100%
100	0%	0%	0%	0%	0%	0%	0%	0%	0%	11%	46%	74%	94%	97%

Table 6: Percentage of years with Heathcote River minimum flow below specified threshold. . Shaded areas show circumstances where the specified flow is always (or never) reached.

Table 5 and Table 6 reveal the progressive reduction in low flow reliability with increasing levels of groundwater abstraction. The same information has been presented in graphical form for inclusion in the Issues and Options report by contouring the lines of equal low flow reliability. For that presentation abstraction changes have been compared to "current" rates rather than 1998/99 totals where the "current" rate has been determined from the 4-year moving average (Figure 11).

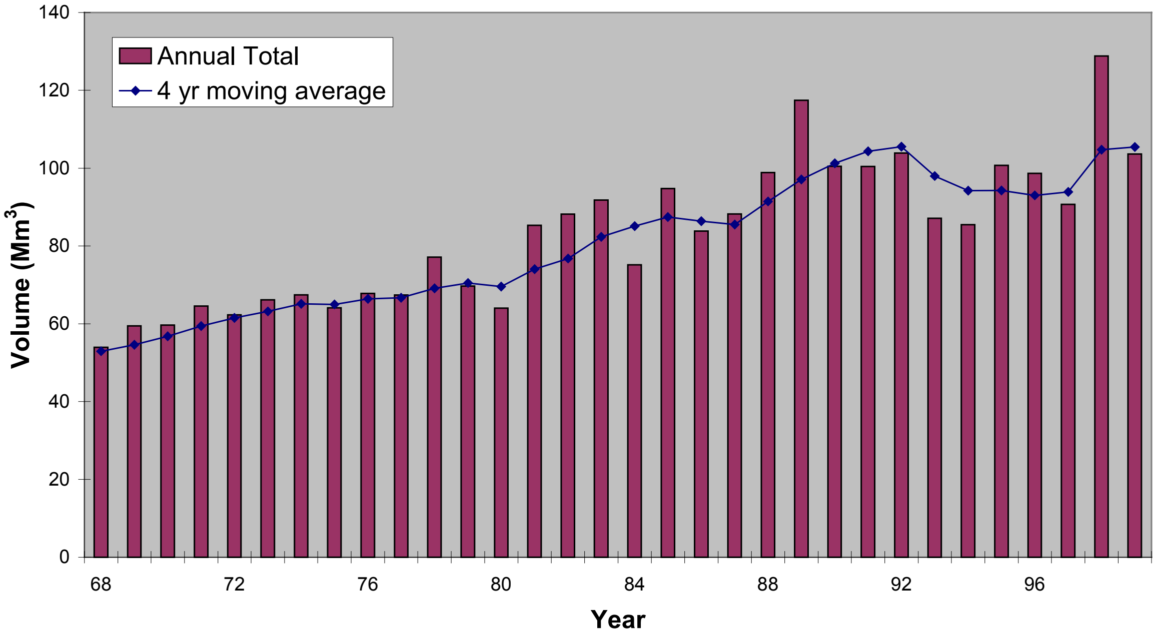

Figure 11: Annual groundwater abstraction (for year ending June).

The graphical presentation of low flow reliability is illustrated in Figure 12 for the Avon River. A restricted range of changes (0 to 50%) in abstraction rate is presented and possible options for minimum desirable flows are indicated: Option 1 (minimum flow of 1300 l/s) was to maintain a minimum flow above what occurs now in a typical summer, Option 2 (minimum flow of 11 l/s) was to accept lower river minimum flows and Option 3 (minimum flow of 900 l/s) was to accept much lower minimum river flows. The use of Figure 12 can be illustrated by considering a particular example: at current abstraction rates Option 2 flow of 1100 l/s is expected to occur less frequently than 1 year in 20 whereas with a 30% increase that flow could be reached 1 year in 2 (highlighted point on graph).

The presentation of the frequency of annual minima for a range of possible levels of groundwater abstraction provides an incomplete picture of the low flow regime since it fails to provide any information about the duration of low flow periods. The duration of the low flow period varies from year to year (depending largely on climatic factors) and the particular groundwater abstraction rate. Table 7 illustrates this for the Avon River subject to a 40% increase in groundwater abstraction and in relation to a low flow threshold of 950 l/s. For this particular case, though the low flow threshold is reached 1 year in 2 on average, the total period during which flows are below 950 l/s is approximately 10% of the time (i.e. 41 months in 35 years).

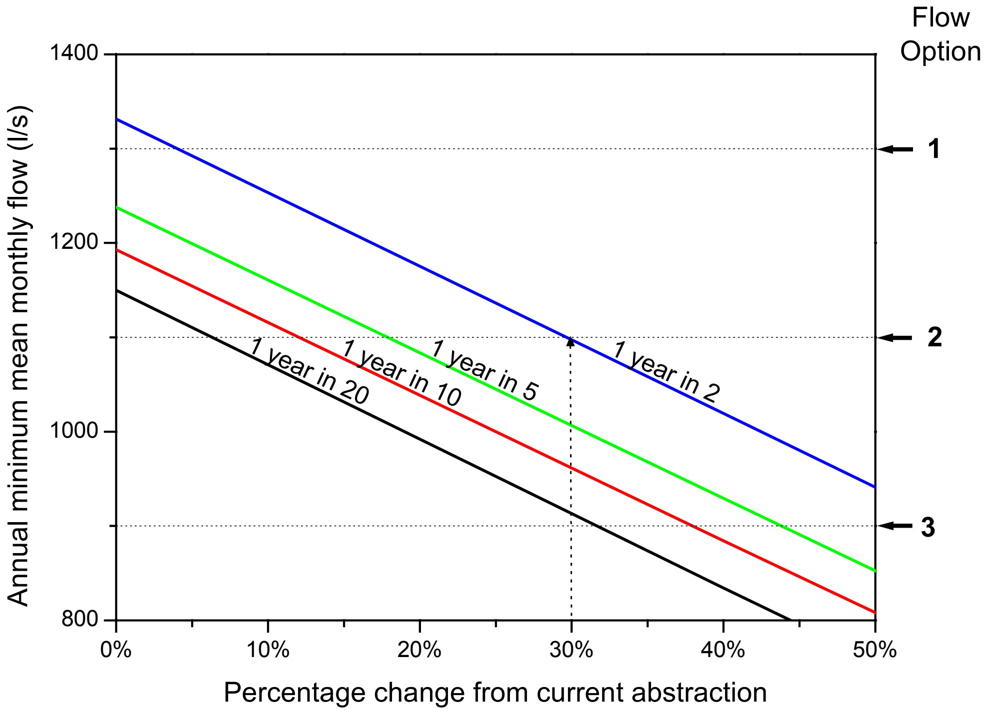

Figure 12: Presentation of low flow reliability data for the Avon River.

Year	Minimum mean monthly flow (l/s)	Duration with flow less than 950 l/s (months)
1969	906	2
1970	883	3
1971	896	4
1972	937	4
1973	894	4
1974	948	3
1983	883	2
1985	926	1
1986	913	1
1988	921	2
1989	908	4
1990	908	2
1991	917	2
1992	937	1
1995	911	2
1998	931	2
1999	892	2

Table 7: Simulated low flow duration for Avon River as a consequence of a 40% increase in groundwater abstraction. (NB: Includes only those years where the specified flow was fallen to).

4.3.2 Case 2 - Effectiveness of constraints on layer 1

Table 8 and Table 9 provide details of low flow reliability for the case where abstraction from layer 1 is fixed and increases in abstraction are met by increasing abstraction from lower layers. Comparison with the equivalent results for the Case 1 simulations indicates that for the Avon River the strategy of restricting abstractions from layer 1 results in an improvement in minimum low flow of around 100 l/s. For the Heathcote River there is comparatively less advantage: at the 0% change the percentage of years with minimum flows below the specified values is unchanged.

Flow (l/s)	Change of abstraction rate relative to 1989/99										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
1400	63%	86%	94%	94%	97%	97%	97%	100%	100%	100%	100%
1300	34%	54%	74%	94%	94%	97%	97%	97%	100%	100%	100%
1200	9%	20%	49%	63%	86%	94%	94%	97%	97%	100%	100%
1100	0%	6%	14%	43%	54%	83%	94%	94%	97%	97%	100%
1000	0%	0%	0%	11%	26%	49%	63%	94%	94%	94%	97%
900	0%	0%	0%	0%	9%	14%	46%	57%	86%	94%	94%
800	0%	0%	0%	0%	0%	0%	11%	29%	49%	66%	94%
700	0%	0%	0%	0%	0%	0%	0%	9%	20%	49%	57%
600	0%	0%	0%	0%	0%	0%	0%	0%	0%	11%	40%

Table 8: **Percentage of years with Avon River minimum flow below specified threshold. Shaded areas show circumstances where the specified flow is always (or never) reached.**

Flow (l/s)	Change of abstraction rate relative to 1989/99										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
700	94%	97%	100%	100%	100%	100%	100%	100%	100%	100%	100%
650	94%	94%	100%	100%	100%	100%	100%	100%	100%	100%	100%
600	91%	94%	97%	100%	100%	100%	100%	100%	100%	100%	100%
550	66%	86%	94%	100%	100%	100%	100%	100%	100%	100%	100%
500	46%	63%	91%	94%	100%	100%	100%	100%	100%	100%	100%
450	17%	40%	77%	94%	97%	100%	100%	100%	100%	100%	100%
400	3%	11%	46%	89%	94%	100%	100%	100%	100%	100%	100%
350	0%	0%	17%	51%	91%	94%	100%	100%	100%	100%	100%
300	0%	0%	0%	20%	54%	91%	94%	100%	100%	100%	100%
250	0%	0%	0%	3%	29%	60%	94%	97%	97%	100%	100%
200	0%	0%	0%	0%	9%	31%	63%	94%	97%	97%	100%
150	0%	0%	0%	0%	0%	0%	20%	51%	91%	94%	97%
100	0%	0%	0%	0%	0%	0%	0%	14%	46%	83%	94%

Table 9: **Percentage of years with Heathcote River minimum flow below specified threshold. Shaded areas show circumstances where the specified flow is always (or never) reached.**

5 Conclusions

The model has been used to simulate groundwater levels and spring flows for a range of different climatic conditions and water use scenarios and interpretation of these results has provided input to the Issues and Options document. However, the most significant outcome of the model study has resulted from a development in conceptual understanding of the system.

Previous descriptions of the Christchurch-West Melton groundwater system presented it as being recharged in the west, becoming confined beneath Christchurch and discharging to the sea at a considerable distance beyond the coast. That general concept tended to generate the impression that groundwater abstraction resulted largely in a reduction of discharge to the sea and that the salt-water interface was a significant distance from the coast. The current modelling study and other related studies in the Woolston/Heathcote area have presented an alternative view:

- The system appears to be dominated by shallow circulation with most of the recharge re-emerging as spring-flow at the margins of the confined aquifer,
- Groundwater abstractions tend to deprive the spring-fed streams of part of their baseflow, and
- The uppermost aquifer is probably discharging vertically upward to the sea closer to the coast than previously thought.

Another insight that has developed from a description of the system dynamics is that climatic variability is probably more significant than the growth in groundwater use.

This revised conceptual model of the system has a number of implications including:

- The active shallow circulation system means that the springs act as “pressure relief valves” and so limit maximum groundwater pressures in the confined area of the system,
- This effect also limits the potential for artificial augmentation to mitigate low groundwater pressures within the confined aquifer,
- Further significant development in groundwater use will reduce the reliability of low flows in the spring fed streams, and
- Management strategies will need to cope with the complications presented by climatic variability to prevent unacceptable declines in pressures and flows.

6 References

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Appendix 1 Estimation of groundwater abstraction

This appendix briefly outlines the procedures used to derive estimates for three different categories of groundwater abstraction: community, industrial/commercial and irrigation.

Community

Groundwater abstraction for community supplies has been assessed from records maintained by the Banks Peninsula District Council and Christchurch City Council along with earlier records from the former Heathcote County, Paparua County, Riccarton Borough and Waimairi County Councils. Abstraction records have been assembled for 120 wells representing the operation of approximately 60 separate pumping stations. In recent years the Christchurch City Council has begun metering the discharge from individual wells. Prior to that the recorded pumping station totals were proportioned amongst the relevant wells on the basis of advice provided by the Council.

The community supply component of total groundwater abstraction includes the industrial/commercial and irrigation uses served by the reticulated systems as well as the domestic demand. In the 1960's and 70's total abstraction for community supply represented about two thirds of the total abstraction. However, this proportion has now fallen to approximately 50%, largely as a result of the growth in irrigation use. Because most of the community use has been metered at pumping stations this component of abstraction is known with a lot more confidence than industrial/commercial or irrigation uses. The combined record for all 120 community wells is illustrated in Figure A2.1

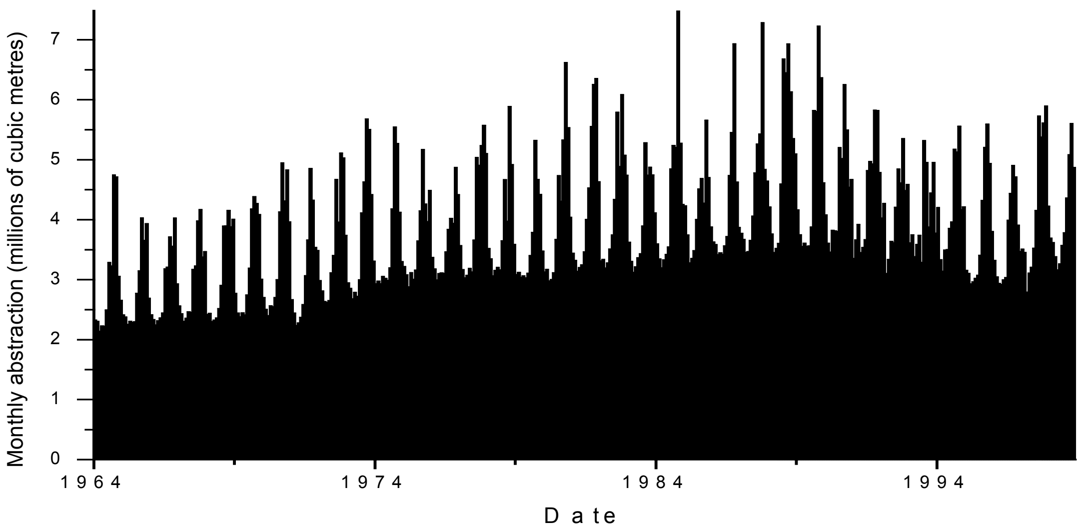


Figure A2.1: Historical pattern of groundwater abstraction for community supply

Industry

Groundwater abstraction for industrial and commercial use has been estimated by surveying consent holders with permitted average flow rates of 7 l/s or more. This flow rate was chosen in an attempt to account for approximately 80% of the total abstraction for this class of use and involves 64 individual wells. In recent years some industrial users have begun to monitor and report their abstraction but for many others the record has relied on estimates derived from consent details and the users. The total industrial/commercial use (excluding that served by the reticulated supplies is approximately 15% of the total and is illustrated in Figure A2.2. Because of the incomplete reporting of this component of groundwater use this record is significantly less accurate than that derived for the community supply.

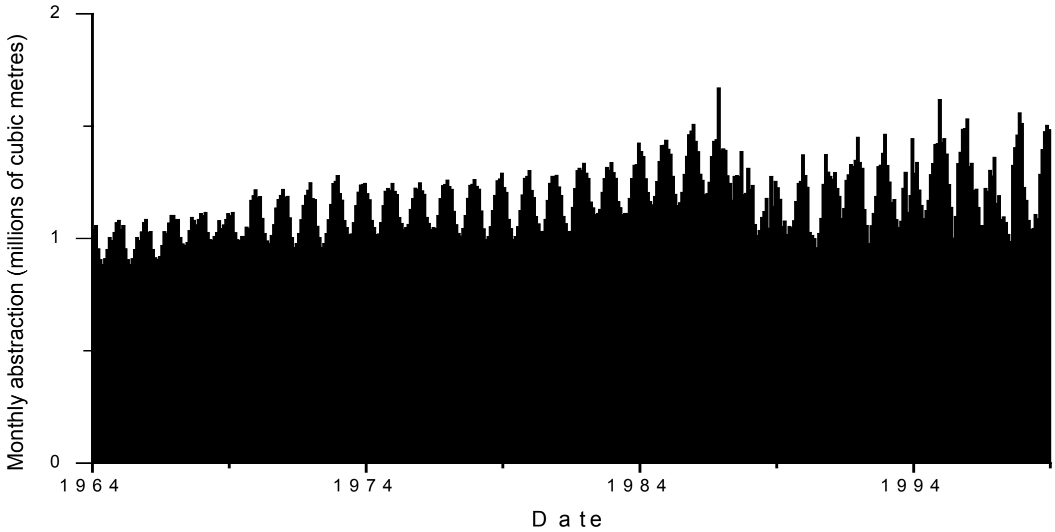


Figure A2.2: Historical pattern of groundwater abstraction for industry

Irrigation

Groundwater abstraction for irrigation has been estimated from details recorded in Environment Canterbury's Consents and Wells databases together with climate records and information about soil characteristics. A total of 947 wells have been assessed as active during the 1965-99 period and abstraction patterns estimated on the assumption that groundwater will have been abstracted at the rate required to satisfy calculated soil moisture deficits. Factors taken into account include:

- the available water holding capacity of the soil in the vicinity of the well,
- daily rainfall and pan evaporation data,
- the irrigable area associated with the well, and
- the maximum flow rate permitted for the well.

The synthesized irrigation abstraction, which once again excludes those applications served by reticulated supplies, has increased from being 10% of the total in the 1960's to around 35%. Because of the seasonal nature of irrigation demand the peak monthly abstraction is considerably greater than for the other uses (Figure A2.3). Since this record is a synthetic one it is significantly less accurate than the estimate for community use. However the record is in reasonable agreement with independent estimates derived from power consumption records for the last four years though it appears to over-estimate the actual use.

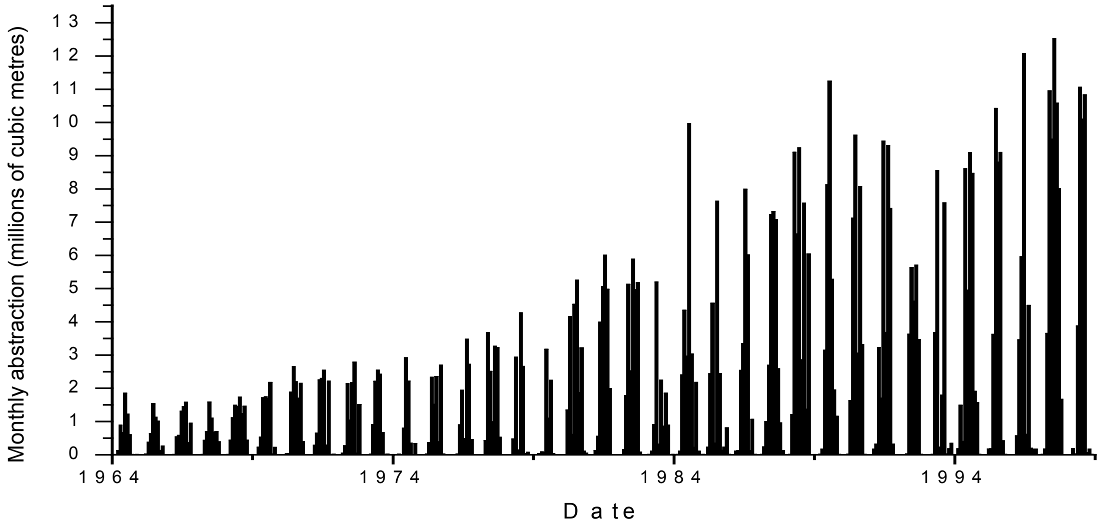


Figure A2.3: Historical pattern of groundwater abstraction for irrigation

Appendix 2 Stream depletion due to hydraulically connected wells

This appendix addresses some of the issues relating to the management of the effects of groundwater abstraction from wells in hydraulic connection with surface water bodies. It explores a basis for extending the concepts currently applied to unconfined aquifers to deal with the issues relating to artesian springs. In this analysis the term "stream depletion" is used to refer to the effect in an unconfined aquifer context whereas the term "spring depletion" refers to the confined aquifer situation.

Stream depletion in unconfined aquifer conditions

Abstracting water from wells has the potential to reduce the flow rate in adjacent streams. This effect, the "stream depletion effect", is dependent on a number of factors including:

- the well discharge rate,
- the duration of the well discharge,
- the distance between the well and the stream,
- the transmissivity and storativity of the aquifer, and
- the presence and properties of any clogging layer in the stream.

The stream depletion effect can be seen as having two distinct characteristics:

- the absolute magnitude of the stream depletion, and
- the degree of connection between the well and stream.

It is possible for a well to be having a significant effect on stream flow yet, at the same time, be so poorly connected that a reduction in pumping rate will yield insignificant improvements. The stream depletion factor (SDF), which is a function of the separation distance and aquifer properties, can be used as a measure of this degree of connection.

Figures A2-1 and A2-2 contrast the way in which different stream depletion factors influence the stream depleting effect. The plots show the increasing effect of continuous pumping and the degree of mitigation of that effect resulting from ceasing pumping after 30 days. For Case 1 with an SDF of 100 days the effects of pumping are so delayed that the impact on stream flow continues to increase even after pumping has stopped and eventually reduces only slowly so that after 30 days without pumping there is still a significant residual effect. In contrast, for Case 2 with an SDF of 1 day the effects of pumping and the subsequent shutdown are relatively rapid and there is a clear mitigation benefit gained by direct control.

Though there is a continuous spectrum of degrees of connection the concept of "hydraulically connected wells" has been developed as a measure to assist with the control of the stream depletion effect. This concept has been applied in an attempt to identify the subset of wells that would provide for relatively direct control of stream depletion. For the Waimakariri River and Opihi River plans an SDF of 100 days has been adopted as the threshold above which nothing is gained (in terms of moderating the stream depletion effect) by enforcing direct controls on pumping rates. This is equivalent to ignoring wells where the stream depletion effect after 30 days pumping is reduced by less than 15% after 30 days of complete cessation of pumping.

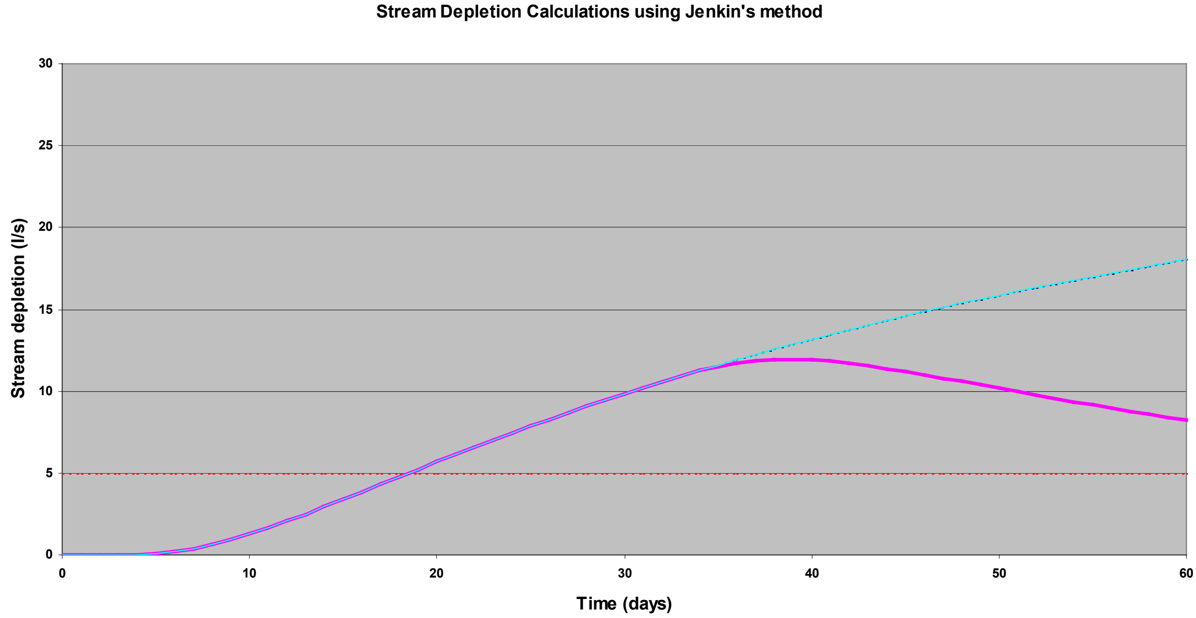


Figure A2-1: Case 1 - Stream depletion effect for well with stream depletion factor of 100 days.

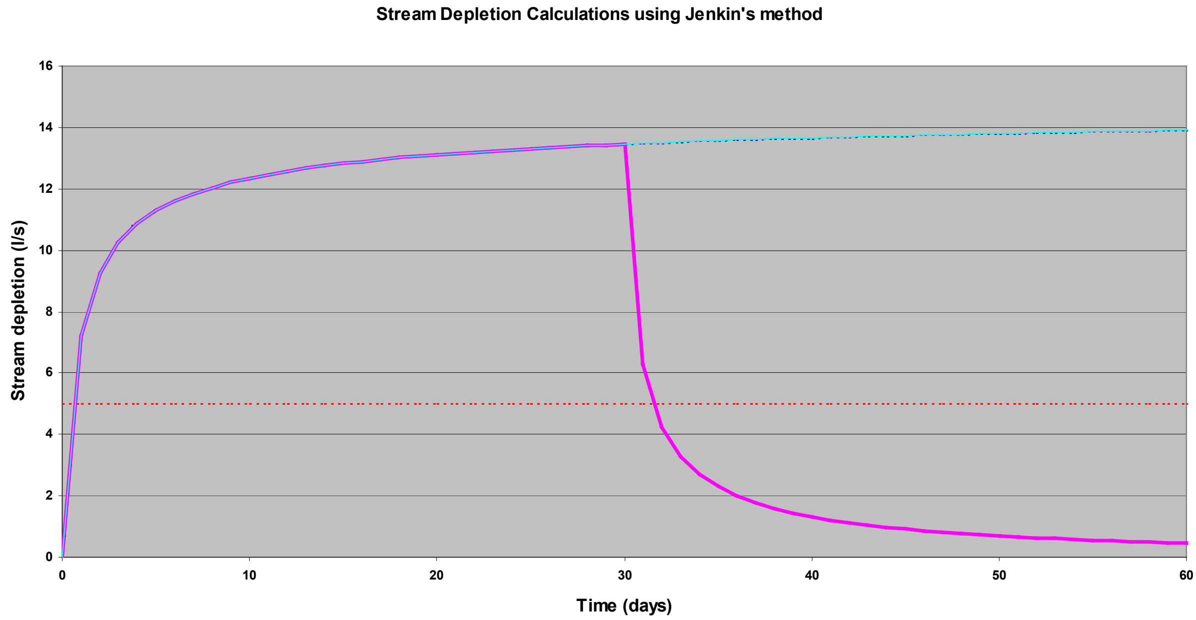


Figure A2-2: Case 2 - Stream depletion effect for well with stream depletion factor of 1 day.

Spring depletion in confined aquifer conditions
There could be merit in applying the stream depletion concepts to managing groundwater takes in the Christchurch - West Melton area. However, the presence of significant springs emerging from confined aquifers adds a slightly different problem requiring separate consideration.

The effects of a well on an artesian spring can be estimated by considering the drawdown at the spring caused by the well discharge. The effect of well discharge on spring flow can be estimated by assuming that in pre-pumping equilibrium conditions the spring flow Q_{s0} is driven by a head difference h_0. For a well at radius r pumping at a rate of Q_w after 30 days the spring flow will have reduced to:

$$Q_{s30} = \frac{Q_{s0}}{h_0}\left(h_0 - \frac{Q_w}{4\pi T}W(u_{30})\right)$$

and, if pumping then ceases, after a further 30 days the spring flow will be given by:

$$Q_{s60} = \frac{Q_{s0}}{h_0}\left(h_0 - \frac{Q_w}{4\pi T}W(u_{60}) + \frac{Q_w}{4\pi T}W(u_{30})\right)$$

where

$$u_t = \frac{r^2 S}{4Tt} \text{ at time t.}$$

The degree of spring depletion mitigation can be expressed as the ratio between the residual depletion effect after 60 days and the depletion occurring at 30 days, i.e:

$$\frac{\Delta_{q60}}{\Delta_{q30}} = \frac{W(u_{30}) - W(u_{60})}{W(u_{30})}$$

This ratio is a function of r^2S/T as shown in Figure A2-3. The parameter r^2S/T has units of days and is somewhat analogous to the SDF: an r^2S/T value of 58 days is equivalent to an SDF of 100 days in terms of the residual effect after 30 days pumping followed by 30 days complete cessation of pumping.

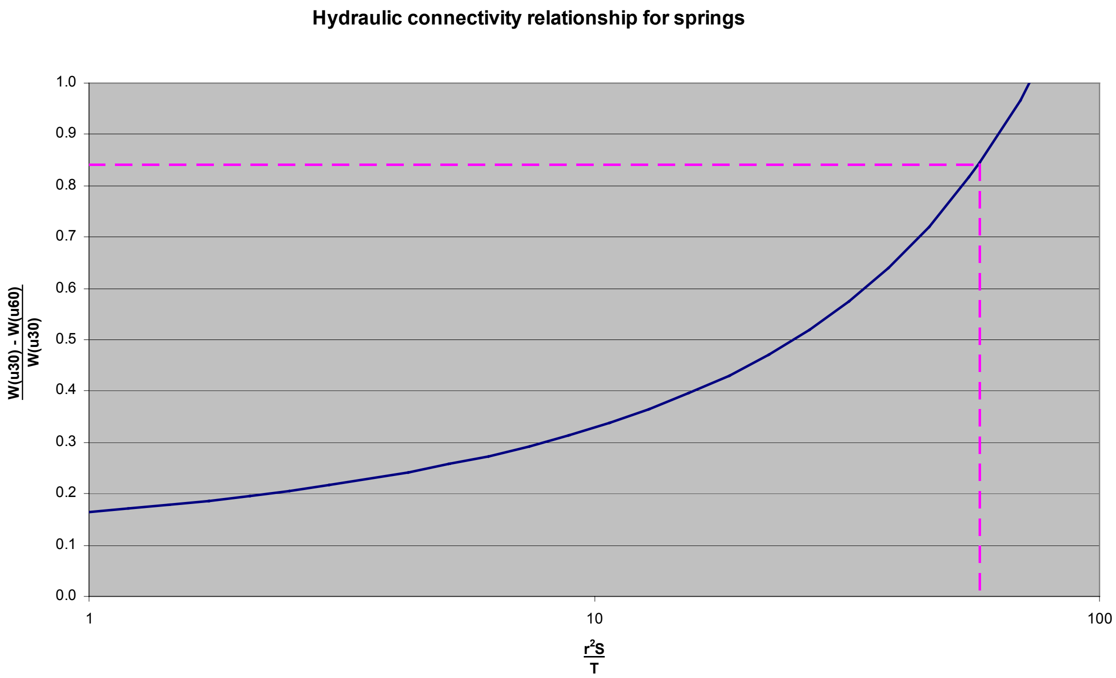


Figure A2-3: Degree of hydraulic connection of a well and spring expressed in terms of the residual effect after 30 days pumping and 30 days shutdown.

Though the stream depletion and spring depletion relationships appear similar they have significantly different implications because of the different storage properties of unconfined and confined aquifers. This can be illustrated for a hypothetical situation where aquifer transmissivity is, say, 1000 m^2/d.

- For stream depletion in an unconfined aquifer situation with a storativity of 0.1 the SDF would equal 100 days when the separation distance equals 1 km.
- For spring depletion in a confined aquifer situation with a storativity of 0.0001 the r^2S/T term would equal 58 days at a separation distance of 24 km.

In the former situation, if the conditions of the Waimakariri River plan applied, wells within 1 km would be regarded as hydraulically connected and subject to direct minimum flow controls while there effect was above a specified minimum value. This measure effectively creates a buffer zone around the stream reaches where stream depletion is an issue.

For the spring condition the lower confined aquifer storativity results in a much more extensive zone; for the example given the zone would encompass all of the Christchurch confined aquifer area. This begs the question of whether it is appropriate to apply the unconfined aquifer stream depletion management approach to the confined aquifer spring depletion situation. Nevertheless, it may prove to be desirable to establish preferred groundwater development zones on the basis that pumping in these zones has less effect on spring flows. The rationale for defining these zones and development of appropriate management strategies requires further investigation.

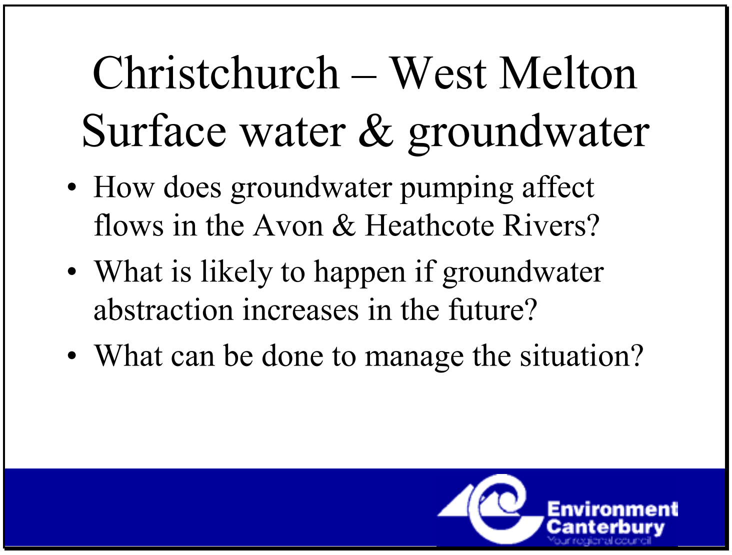
Appendix 3 Saltwater intrusion – seawater contamination

All the confined aquifers appear to extend beyond the coastline and the stratigraphy of offshore sediments has suggested that Aquifer 1 may outcrop to the sea at a considerable distance offshore. On the basis of this evidence it had been considered that discharge mainly occurs via Aquifer 1 at the offshore outcrop about 40km from the coast. Recent investigations of groundwater quality problems in the Woolston/Heathcote area have led to a significant re-appraisal of the available data and it now appears that Aquifer 1 may be discharging through the uppermost confining layer and that, as a consequence, the interface between freshwater and seawater may be located only 3 to 4 km from the coast.

Without direct evidence of the presence of saltwater any estimates of the freshwater/saltwater interface position are inevitably uncertain. In those circumstances it is appropriate to take a precautionary approach to managing the risk of future contamination. This could be done by designating a groundwater coastal zone within which abstractions would be managed with the objective of limiting future encroachment of saltwater. This would require on-going monitoring of pumped production wells and passive sentinel wells and would allow future revision of abstraction limits as information and understanding improved. A possible management approach would be to ban pumped abstraction from Aquifer 1 within a 5 km coastal protection zone (i.e. limit abstractions to those provided by free-flowing artesian wells). Environment Canterbury is currently extending its capacity to monitor groundwater pressures and quality in response.

Appendix 4 Presentation prepared for public consultation

Slide 1

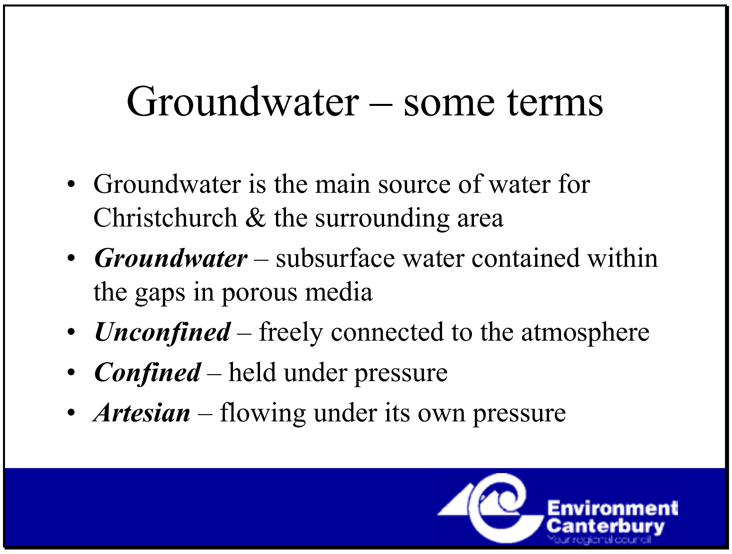


Introduction

The main objective of the study of Christchurch – West Melton surface water and groundwater has been to gain a better understanding of the relationship between groundwater pumping and the flows in the spring fed streams. The questions that have provoked the investigation include things such as:

- How does groundwater pumping affect flows in the Avon and Heathcote Rivers?
- What is likely to happen if groundwater abstraction increases in the future?
- What can be done to manage the situation?

Slide 2



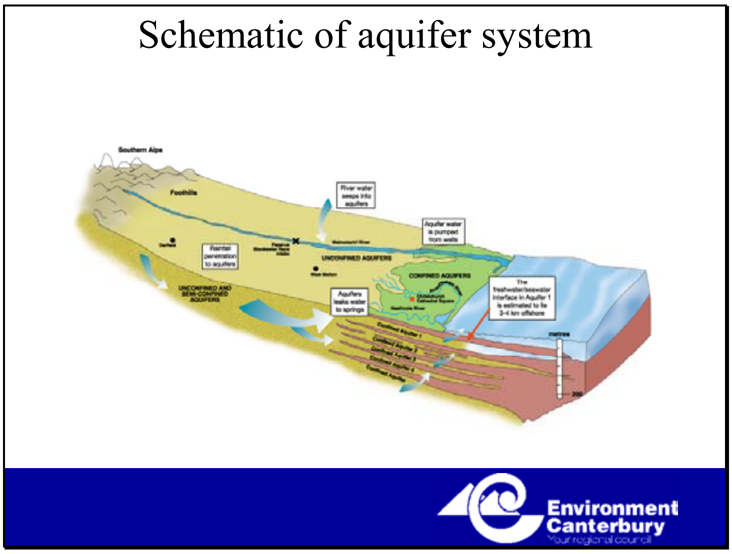
Groundwater – some terms
Before going into the details of our investigation I'd like to introduce some basic principles about groundwater.

Firstly, as most Christchurch citizens proudly know, the water supplies for Christchurch and the surrounding area are obtained almost entirely from groundwater. ***Groundwater*** refers to the water contained within the gaps between subsurface material such as gravel and sand. So, if we pour this surface water (jug) into the gravel in this container it becomes, by definition, groundwater. In this state, with the upper surface freely connected to the atmosphere the groundwater is described as being ***unconfined.*** The water level in a well will be at the same level as that upper surface and when water is pumped it drains water from the spaces between the particles.

If the groundwater lies beneath a relatively impermeable (confining) layer it can be held under pressure and is then referred to as being ***confined***. In that case the water level in a well will rise above the top of the aquifer and, if the pressure is high enough will flow naturally. This water is released by the decompression of the groundwater while the subsurface material remains fully saturated. So, if I pressed hard enough on this plastic confining layer and then punctured the seal, some water would flow upward as an ***artesian*** well does.

Finally, the term ***aquifer*** is used to refer to a groundwater source that will yield significant quantities of groundwater to wells or springs.

Slide 3



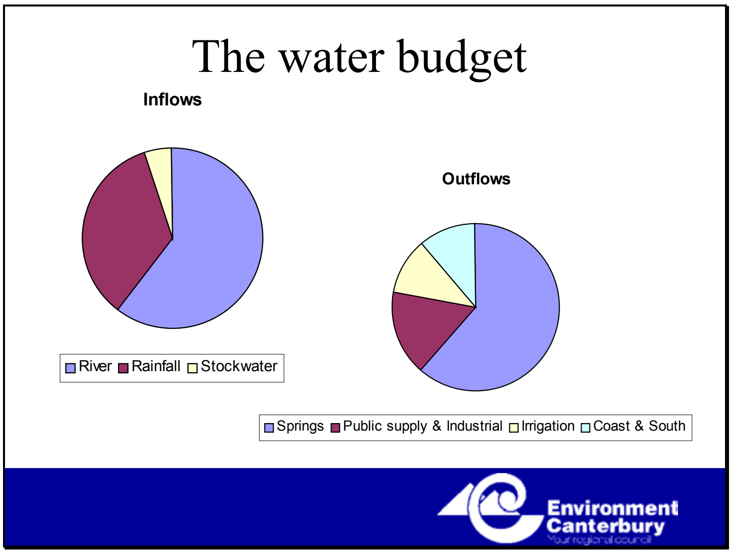
Schematic of aquifer system
Groundwater occurs in the unconfined and confined conditions within the Christchurch area as shown in this schematic diagram. Note the vertical exaggeration. In the west the aquifers are unconfined and the groundwater is recharged by seepage from the Waimakariri River, from rainfall on the plains and, to a small extent, from leakage and return flows from stockwater races.

To the east, a sequence of layers of relatively fine sediment form confining layers (sometimes referred to as a club sandwich) which restricts the flow of water to the sea. The consequence of that is most of the water re-emerges in springs to supply the Avon and Heathcote Rivers (and the other spring fed streams – the South Branch, Styx & Halswell). In the confined aquifer area pressures increase with depth and many deeper wells have sufficient pressure to produce artesian flows.

There is almost no direct information about the aquifer structure beyond the coast but the available data suggests that there is a relatively small outflow to the sea and that groundwater in the lower aquifers must seep upwards through the sequence of confining layers before it is able to discharge to the sea.

This particular physical setting means that the springs of the Avon and Heathcote Rivers act as pressure relief valves for the confined aquifer. Groundwater levels fluctuate over a wide range in the unconfined area in response to rainfall but at the margin of the confining layers higher pressures are relieved by higher spring flows and, as a consequence, the groundwater pressures within the confined aquifer area are constrained.

Slide 4



The water budget
These charts show our estimate of the current average water budget for the area under investigation.

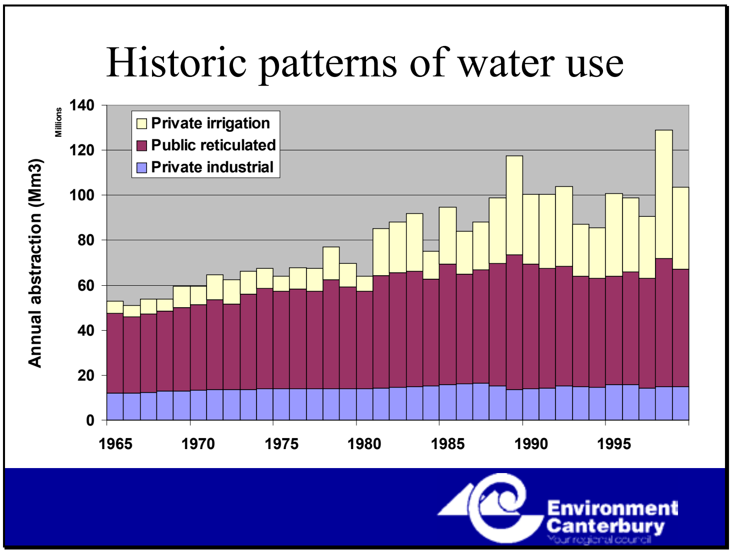
Inflows to the system occur primarily over the unconfined aquifer area to the west of the city. Leakage from the Waimakariri River provides the single largest contribution (approximately 60%) and this occurs at a relatively steady rate. Rainfall recharge is much more variable being seasonal and dependent on wet winters. On average it is about 35% of the total recharge but in a dry winter may be negligible. In addition to these two major components there is a small contribution (about 5%) from stockwater race leakage & return flows.

Outflows from the system include the natural losses and the abstractions from wells. The natural outflows take the lion's share with about 55% going to the springs on the margin of the confined aquifers and a further 20% discharging to the coast and to the south of Banks Peninsula.

The balance of the outflow goes to wells, with about 15% going to public reticulated supply and private industry and the remaining 10% going to irrigation which is primarily taken from the unconfined aquifer area.

All these water budget components vary in response to climate patterns and to the level of demand.

Slide 5



Historic patterns of water use
We can look in a little more detail at how water use has changed over the years. This plot shows our estimate of the annual totals for:
- Private industrial
- Public reticulated water supply, and
- Private irrigation

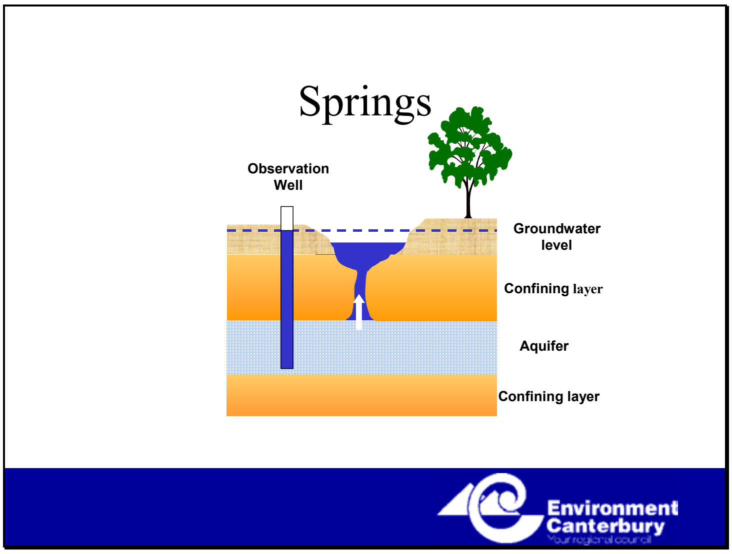
The total use has more than doubled since 1965 but there are significant differences between the various types of use.

Industrial use appears to have been relatively stable and, overall, doesn't vary markedly on a seasonal basis.

The public water supply, which includes industries which take water from the reticulated system increased steadily from 1965 to 1985. Since then, however, the total abstraction has stabilised despite the increasing population. This is due to many different factors including the in-filling, which reduces demand for garden watering, and a range of conservation initiatives of the City Council.

Irrigation use has increased sharply since the early 80's. This use is concentrated in the summer months when low soil moisture levels are low. Total use varies from year to year depending on the total number of irrigators and the growing season climate conditions.

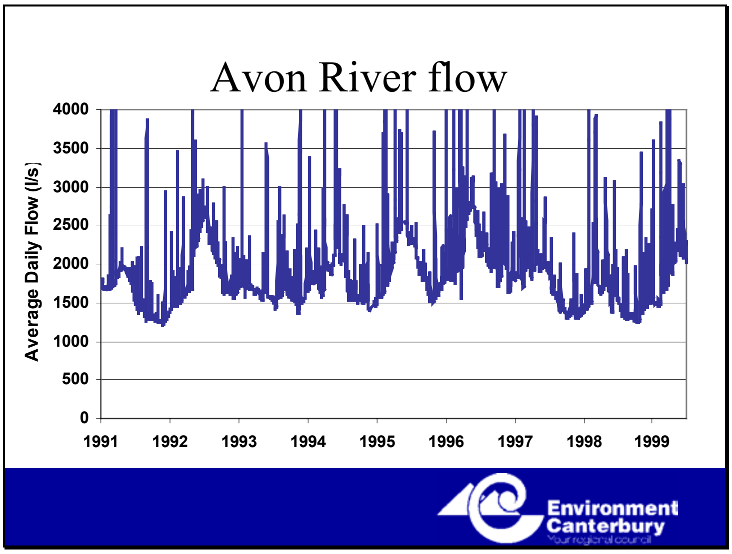
Slide 6



Springs

Since the rest of this talk is going to focus on the way in which groundwater abstractions affect flows in the Avon & Heathcote Rivers I'd like to begin by describing the behaviour of springs. This schematic cross-section illustrates one particular type of spring where the pressure in a confined aquifer causes groundwater to discharge upwards through a vent in a streambed. This type of spring is common along the margins of the confined aquifer and the rate of flow is influenced by the groundwater level in a way that is demonstrated when we pull the plug on our groundwater model – while the water level is high the flow is relatively vigorous but this quickly reduces as the water level falls.

Slide 7

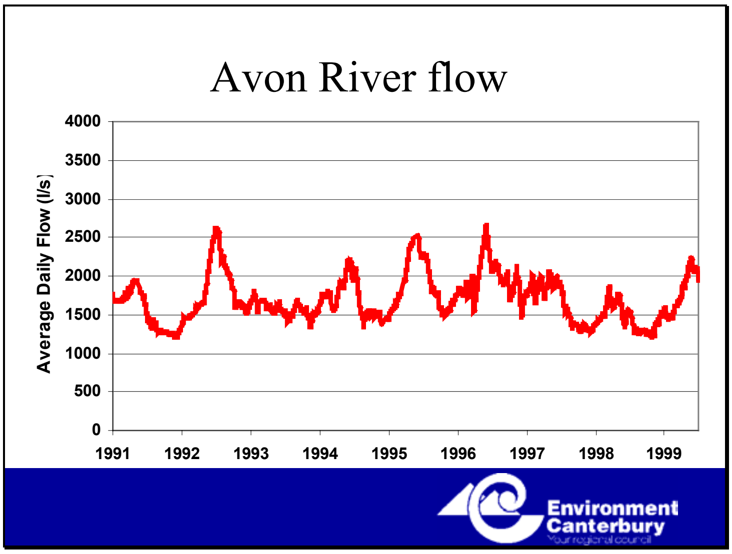


Avon River flows

The contribution that spring flow makes to the Avon River can be seen in this plot showing how river flow has varied since 1991. The graph shows date along the horizontal axis and average daily flow in litres per second on the vertical axis. The blue spiky line shows the total flow in the river – each spike shows a flood, but because of the high proportion of impermeable area in the catchment (roofs, roads and other sealed areas) the river flow quickly returns to the pre-flood base flow.

If we trace along the bottom of all the spikes, as shown here, we can highlight the way in which that base flow has varied over the year. The shaded area represents the combined effect of spring flows to the river. That flow varies from year to year depending on groundwater levels. Summer low flows have varied over these 9 years with the lowest flow of about 1210 l/s at the end of the 1992 summer.

Slide 8



Avon River flows

Environment Canterbury maintains a continuous record of flow in the Avon River at the Gloucester St bridge (near the library). The contribution that spring flow makes to the Avon River can be seen in this plot showing how river flow has varied since 1991. The graph shows date along the horizontal axis and average daily flow in litres per second on the vertical axis. The blue spiky line shows the total flow in the river – each spike shows a flood, but because of the high proportion of impermeable area in the catchment (roofs, roads and other sealed areas) the river flow quickly returns to the pre-flood base flow.

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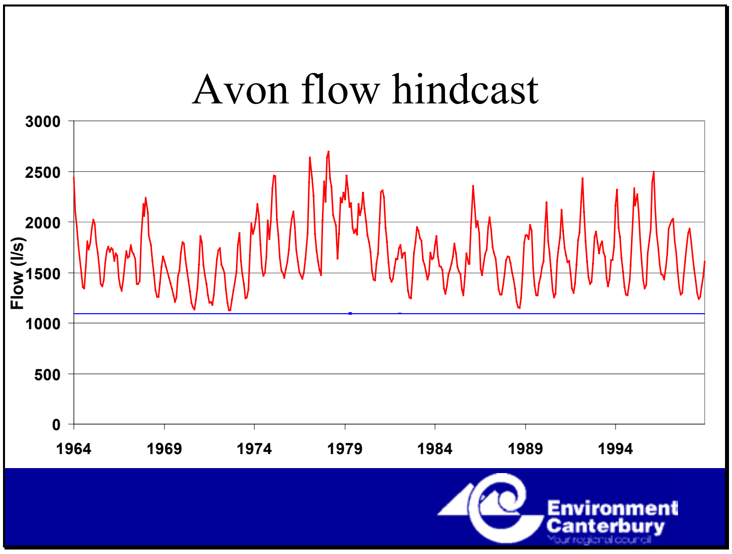
Slide 9

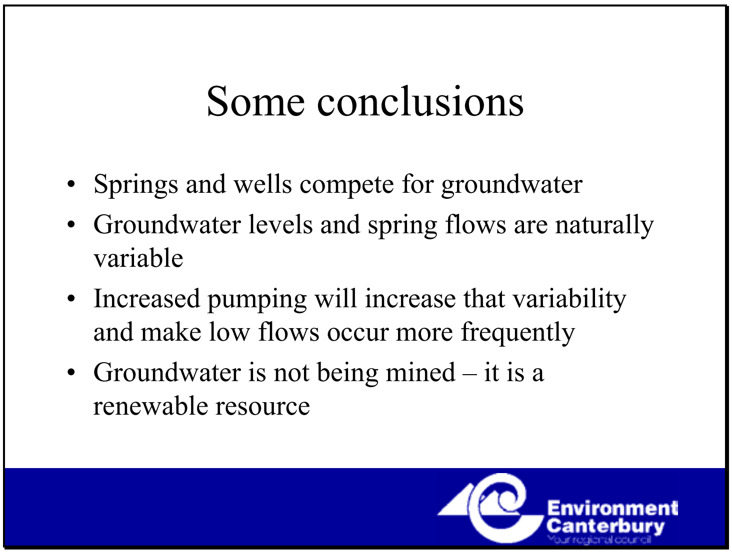


Avon flow hindcast

We have developed a computer model of the groundwater system which allows us to estimate the spring flows that would occur with various levels of demand over a range of climate conditions. This graph is really a hindcast – it shows the spring flows that could have been expected if the current level of groundwater use in Christchurch and the surrounding areas had applied over the last 35 years.

The plot shows an annual cycle with summer low flows falling close to 1100 l/s (the ochre line which represents Option 2) on three occasions during that period. It's worth noting that the sequence of years with low flows corresponds to a dry period at the beginning of the 1970's which may have been the driest since records began in the mid-1800's.

Slide 10



Some Conclusions

I'd like to conclude by noting some of the most important concepts that have emerged from our investigations:

Firstly, it seems clear that the springs and wells, to a large extent, compete for the same groundwater. Increasing abstractions from wells will result in a reduction of discharge to the spring-fed streams.

However, groundwater levels and spring flows vary naturally – increased pumping will increase that variability with the result that low flows will occur more frequently.

Finally, we are not facing a situation where groundwater is being mined. Groundwater is a renewable resource and we are not depriving future generations by using groundwater now. However, if as a community we develop high water use patterns we increase the risk of unacceptable environmental consequences.

Appendix 5 Safe yield – then and now

The results described in this report have been compared to previous assessments of safe yield. The following note was prepared to clarify the differences between the two assessments.

In the 1986 Report, the effects considered for the "safe yield" concept were:

- ***decline in groundwater levels***
- ***decrease in springflow***
- ***interference between bores***
- ***inflow of poor quality recharge water***
- ***over-pumping and subsidence***
- ***reversal of present upwards hydraulic gradient***
- ***sea water intrusion.***

All of these effects are commonly assessed in groundwater studies and, except for the last one, were occurring to some degree in 1986, and are still occurring today.

The 1986 Report said that "It has not been possible, at this stage, to quantify the safe yield…", and that because predictions in 1986 that total abstraction would double by the turn of the century (i.e. by year 2000), it was paramount to do the detailed mathematical computer modelling to predict the consequences of the increasing abstraction. The predicted doubling of total abstraction was not, in 1986, seen as sustainable.

However, we felt that, in 1986, we were confident enough to signal an "interim safe yield". We also recognised that any increase in abstraction would further exacerbate the above effects, but judged that, within the recommended abstraction limits, the degree of adverse effects would be acceptable.

The 1986 study reported estimated actual abstraction over the Christchurch City area for the 1984/85 year as having been 111 million cubic metres (MCM): the proposed interim limit was approximately 30% higher than that figure. The critical thing to understand about the 1986 estimated abstraction, the predicted year 2000 abstraction, and the "interim safe yield"; is that they are all relative, were assumed to have the effects measured in 1986 (which was the base for calculations), and that the estimated effects of increased abstraction (called the "interim safe yield") were acceptable. The current study has re-assessed historic water use and concluded that, over the equivalent area, actual abstraction for 1984/85 was approximately 69 MCM (most of the difference in the two figures is related to the way in which irrigation water use has been estimated). The various estimates of abstraction are summarized below:

Annual abstraction (Million Cubic Metres)

	1986 Assessment	***Current Assessment***
1984/85 abstraction	***111***	***69***
"Interim Safe Yield" (+ 30%)	***143***	***90***[1]
1998/99 abstraction		***69***[2]
Estimated 2020 abstraction (high growth, dry year)		***87***

In terms of the 1986 Report, there would be room for a significant increase in total abstraction before the "interim safe yield" was reached. However, this assumes that the effects of the increased abstraction would be acceptable. It is this crucial aspect that we are assessing with the new calculations and on which we are about to seek public input.

The "critical effect" that we now know will occur is a decrease in springflow resulting in a reduction in flows in the Avon and Heathcote Rivers. This is largely an amenity issue. It is clear that the other effects relating to the physical sustainability of the groundwater resource (e.g. over-pumping, reversal of upwards hydraulic gradient, see water intrusion) will remain relatively localized issues if springfed rivers are not substantially depleted. Clearly, the groundwater resource can supply greater quantities than at present before these other effects occur.

The critical question is, therefore, how low and for how long would residents accept the Avon and Heathcote Rivers' flows to go as against their desire to abstract sufficient groundwater for whatever their desired purposes (e.g. garden watering during some summer periods).

[1] This is simply a restatement of the 1986 estimate relative to the re-assessed 1984/85 abstraction, i.e. 30% increase from 69MCM.
[2] Assessed abstraction over the Christchurch City area was approximately the same in the 1984/85 and 1998/99 years.

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