TECHNICAL MEMORANDUM

APPROACH TO DELINEATE SUBTERRANEAN STREAMS AND DETERMINE POTENTIAL STREAMFLOW DEPLETION AREAS

POLICY FOR MAINTAINING INSTREAM FLOWS IN

NORTHERN CALIFORNIA COASTAL STREAMS

FEBRUARY 28, 2008

STETSON
ENGINEERS INC.

TABLE OF CONTENTS PAGE

LIST OF TABLES

LIST OF FIGURES FOLLOWS PAGE

APPENDICES

APPROACH TO DELINEATE SUBTERRANEAN STREAMS AND DETERMINE STREAMFLOW DEPLETION AREAS

The State Water Resources Control Board's (State Water Board) adoption of the Policy for Maintaining Instream Flows in Northern California Coastal Streams (Policy) may result in some water diverters choosing to divert groundwater instead of pursing a water right application to divert water from surface streams. Groundwater diversions can have similar effects on the depletion of surface flow as diversions from surface streams. Thus, increased groundwater pumping could have a negative effect on the instream flows and anadromous fish habitat in the policy area if a hydraulic connection exists.

Pursuant to Water Code 1200, the State Water Board has permitting authority over subterranean streams flowing in known and definite channels. Groundwater classified as percolating groundwater is not subject to the State Water Board's permitting authority. Thus, when considering an appropriation of groundwater, the State Water Board may have to evaluate the legal classification of the groundwater and determine whether it is a subterranean stream subject to the State Water Board's permitting authority. In doing so, the State Water Board applies a four-part test, which was uphold by the appellate court in *North Gualala Water Co. v. State Water Resources Control Bd.* (*North Gualala*) (2006) 139 Cal.App.4th 1577 [43 Cal.Rptr.3d 821]. The State Water Board also has continuing authority to protect public trust uses and to prevent the waste, unreasonable use, unreasonable method of use, or unreasonable method of diversion of water, regardless of basis of right.

This technical memorandum provides an approach: (1) to delineate subterranean streams in accordance with the State Water Board's four-part test; and (2) to delineate areas (Potential Stream Depletion Areas) where groundwater pumping could potentially cause stream depletion. The identification of Potential Stream Depletion Areas (PSDA) is not intended as a substitute for the State Water Board's classification of groundwater; instead, identification of a PSDA may be used to assess impacts of groundwater pumping on instream flows and habitat. New information and site specific studies may in the future result in some PSDA being classified as subterranean streams. The named groundwater basins/areas in the Policy area are listed in Table 1.

TABLE 1
LISTED GROUNDWATER BASINS IN THE POLICY AREA [1]

State Basin/Sub-Basin Designation	Groundwater Basin/Area Name	Watershed
1-19	Anderson Valley	Navarro River
1-20	Garcia River Valley	Garcia River
1-21	Fort Bragg Terrace Area	---
1-28	Mattole River Valley	Mattole River
1-29	Honeydew Town Area	Mattole River
1-37	Cottoneva Creek Valley	Cottoneva Creek
1-40	Ten Mile River Valley	Ten Mile River
1-41	Little Valley	Ten Mile River
1-42	Sherwood Valley	Ten Mile River
1-45	Big River Valley	Big River
1-46	Navarro River Valley	Navarro River
1-49	Annapolis Ohlson Ranch Formation Highlands	Gualala River
1-50	Knights Valley	Russian River
1-51	Potter Valley	Russian River
1-52	Ukiah Valley	Russian River
1-53	Sanel Valley	Russian River
1-54	Alexander Valley	
1-54.01	Alexander Area	Russian River
1-54.02	Cloverdale Area	Russian River
1-55	Santa Rosa Valley	
1-55.01	Santa Rosa Plain	Russian River
1-55.02	Healdsburg Area	Russian River
1-55.03	Rincon Valley	Russian River
1-56	McDowell Valley	Russian River
1-57	Bodega Bay Area	---
1-59	Wilson Grove Formation Highlands	---
1-60	Lower Russian River Valley	Russian River
1-61	Fort Ross Terrace Deposits	---
2-1	Petaluma Valley	Petaluma River
2-2	Napa-Sonoma Valley	
2-2.01	Napa Valley	Napa River
2-2.02	Sonoma Valley	Sonoma Creek
2-2.03	Napa-Sonoma Lowlands	---
---	Napa-Sonoma Volcanic Highlands	Napa River
2-19	Kenwood Valley	Sonoma Creek
2-27	Sand Point Area	---
2-28	Ross Valley	Corte Madera Creek
2-29	San Rafael Valley	---
2-30	Novato Valley	Novato Creek

[1] Source: Modified from California Department of Water Resources, October 2003, California's Groundwater: Bulletin 118, pp. 120-121.

DELINEATION OF SUBTERRANEAN STREAMS

In determining the legal classification of groundwater, the following physical conditions must exist for the State Water Board to classify groundwater as a subterranean stream flowing through a known and definite channel:

(1) A subsurface channel must be present;

(2) The channel must have a relatively impermeable bed and banks;

(3) The course of the channel must be known or capable of being determined by reasonable inference; and

(4) Groundwater must be flowing in the channel.

Where the above physical criteria can be clearly applied, the subterranean stream may be identified using published resources and approaches as discussed below.

The delineation of the bed and banks of a subterranean stream should consider all available pertinent information, primarily geology, soils and topography. The delineation of the bed and banks of a subterranean stream shall be conducted by using the following information and procedure.

1. **Map Base**. Establish a topographic base map with a reasonable scale that is available throughout a watershed. The USGS 7.5 minute topographic quadrangle map with a contour interval of no greater than 40-feet should serve as that base map.

2. **Informational Data Base**. Collect and review mapped and published geologic information by the USGS and the California Geological Survey (CGS) at scales deemed appropriate to serve as the primary basis for locating the contact between relatively impermeable bedrock and Holocene/Recent alluvial deposits (or equivalent deposits) clearly associated with and in reasonable proximity of a stream. This geologic contact between bedrock and Holocene/Recent alluvium is considered the bed and banks of the subterranean stream. Other geologic sources should be evaluated for appropriateness. The sources of geologic data that may be utilized are included as Appendix A. Where useful geologic information is not currently available, mapped soil types determined by Natural Resources Conservation Service (NRCS) to be associated with subterranean streams, may be utilized as a guide to identifying bed and banks.

3. **<u>Topographical Adjustment</u>**. Subsequent to overlaying the available geologic and/or soils data on the 7.5 minute topographic maps, the boundaries between the alluvial deposits can be adjusted based upon topographic expression. Minimal adjustments are likely required even when the data sources transferred to the maps have been rectified. Mapping of contacts between different geologic or soil units either in the field or using aerial photography cannot be expected to match the topographic base at all locations without adjustments. If only regional geologic maps are available, topographic expression used in conjunction with soil maps may be the primary tool to delineate subterranean streams.

4. **<u>Field Inspection</u>**. Along stream reaches where data are limited and/or conflicting, an independent field inspection by a qualified geologist or engineer should be conducted.

MAPPING OF SUBTERRANEAN STREAMS

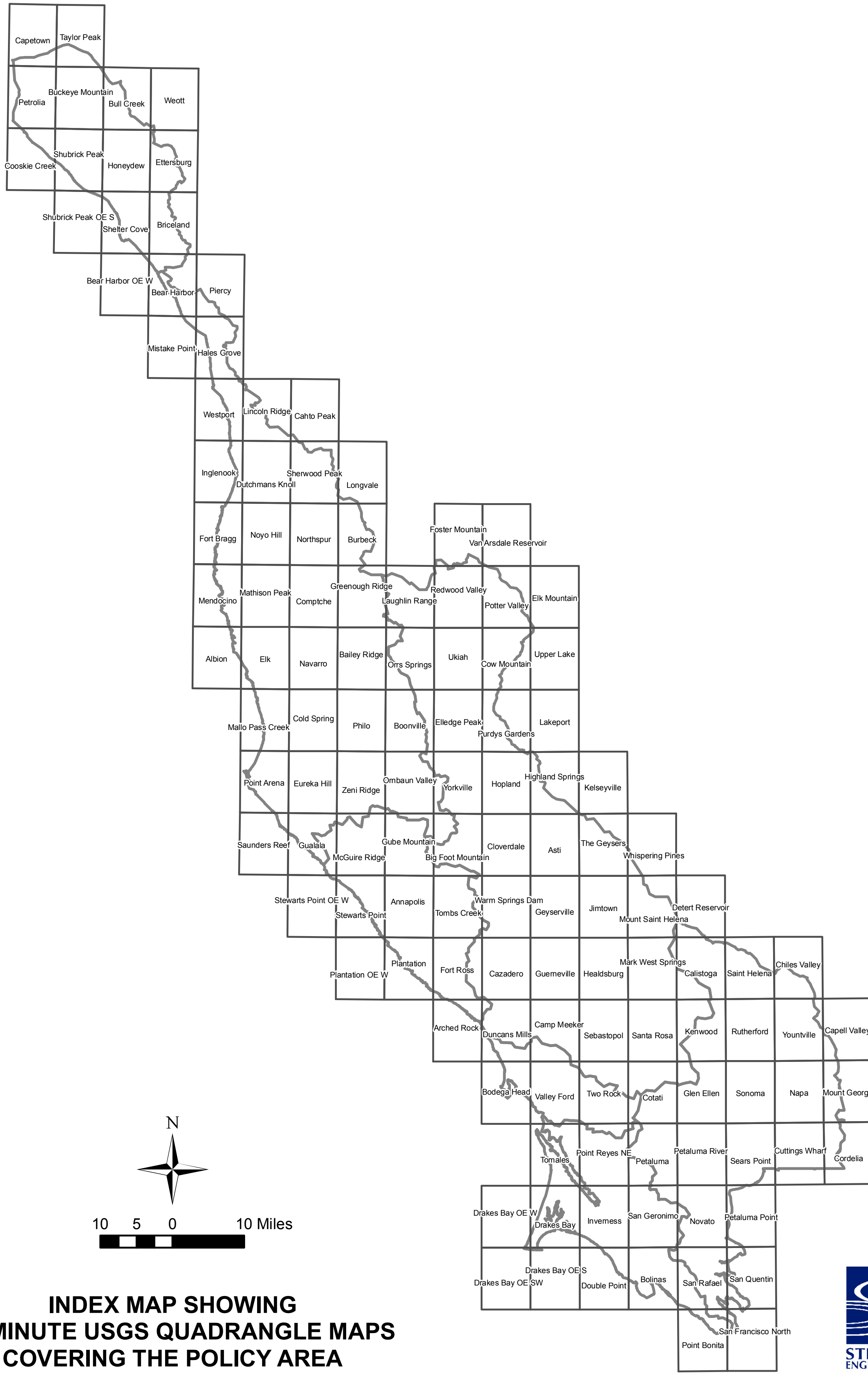
The Policy Area is encompassed in all or parts of 128 USGS 7.5-minute topographic quadrangle maps identified on Figure 1. Each map will be reviewed in conjunction with available geologic and soils maps to delineate subterranean streams and/or PSDA. Using the best available information, the subterranean streams and PSDA will be delineated on USGS 7.5-minute topographic quadrangle maps. Four types of situations are expected, depending upon local conditions in a given mapped area:

- Maps with only subterranean stream reaches delineated;
- Maps with only PSDA delineated;
- Maps with both subterranean stream reaches and PSDA delineated; and
- Maps without either delineated subterranean stream reaches or PSDA.

Individual maps will be prepared for those quadrangles that include delineated subterranean streams and/or PSDA. The quadrangle maps without either delineated subterranean streams or PSDA will be indicated on an index map. Individual maps will not be produced for those quadrangles without delineated subterranean streams or PSDA.

The subterranean stream and PSDA delineations prepared in conjunction with this project will be based on the available geologic information at the time of delineation. Further refinement of the delineations could be made in the future if new information becomes available. Field inspection will not be conducted as part of the delineations. Therefore, the following statement will be included on all maps resulting from this project to insure that no alluvial deposits associated with a "natural channel" are excluded from the jurisdiction of the State Water Board.

FIGURE 1



INDEX MAP SHOWING
7½ MINUTE USGS QUADRANGLE MAPS
COVERING THE POLICY AREA

Because the delineated areas on this map were based on information readily available at the time of its development, this map does not claim to represent all of the subterranean streams or potential stream depletion areas that exist in the area. Site specific investigations will be needed to verify the existence of subterranean streams or potential stream depletion areas.

Throughout much of the Policy Area, delineated subterranean streams are characterized by tight channels with steep slopes, particularly in remote portions of the watersheds. Many of those reaches are not accessible to well drilling equipment and, therefore, the likelihood of significant development of subterranean flow is remote at this time. Furthermore, if access is possible at some locations in these narrow canyons, the diversions facilities, i.e. well, pumping equipment and appurtenances, piping, etc, could be subject to flood damage. Since the scale (1:24,000) of the maps that will be used to delineate subterranean streams for this project is not small enough to show all the roads that may be present in the undeveloped portions of the watersheds, it will be necessary for the State Water Board to review smaller scale maps or small scale aerial photographs to determine the likelihood and potential extent of future diversion of subterranean flow in these remote areas. Such reviews will need to be conducted periodically as development in the region increases. At the present time the use by the State Water Board of the 1:24,000 scale maps in conjunction with its local knowledge should be adequate to estimate the potential number of new water right applications that may be generated under the Policy.

STREAM DEPLETION WHERE SUBTERRANEAN STREAMS ARE NOT DELINEATED

In the Policy area where streams and adjacent alluvial aquifers are hydraulically connected, groundwater pumping threatens streamflow by depletion. Stream depletion from wells can result from direct depletion of the stream or reduction of groundwater flow to the stream. Groundwater moves laterally from older alluvial deposits to the stream channel deposits and is then discharged to the stream as baseflow. Wells pumping from the older alluvial deposits will intercept groundwater moving toward the stream which may ultimately discharge to the stream. Where geologic maps indicate or infer the presence of older alluvium (or equivalent deposits), the location and nature of the “bed and banks” becomes uncertain. Therefore, along stream reaches where geologic map information is currently insufficient to definitively delineate “bed and banks” (subterranean stream), but extraction of groundwater can potentially deplete streamflow, Potential Stream Depletion Areas (PSDA) will be delineated. New information and site specific studies may result in some PSDA being classified as subterranean streams.

The areal extent of stream channel deposits of an active natural stream within a PSDA, as mapped by the USGS or CGS, will be indicated on the maps prepared for the Policy area. These deposits typically occupy all or a portion of the stream floodplain and were deposited by the stream. Pumping from these deposits are likely to result in depletion rates higher than rates resulting from pumped wells located elsewhere in a PSDA. A schematic diagram showing the relationship between subterranean streams, PSDA and stream channel deposits is shown in Figure 2.

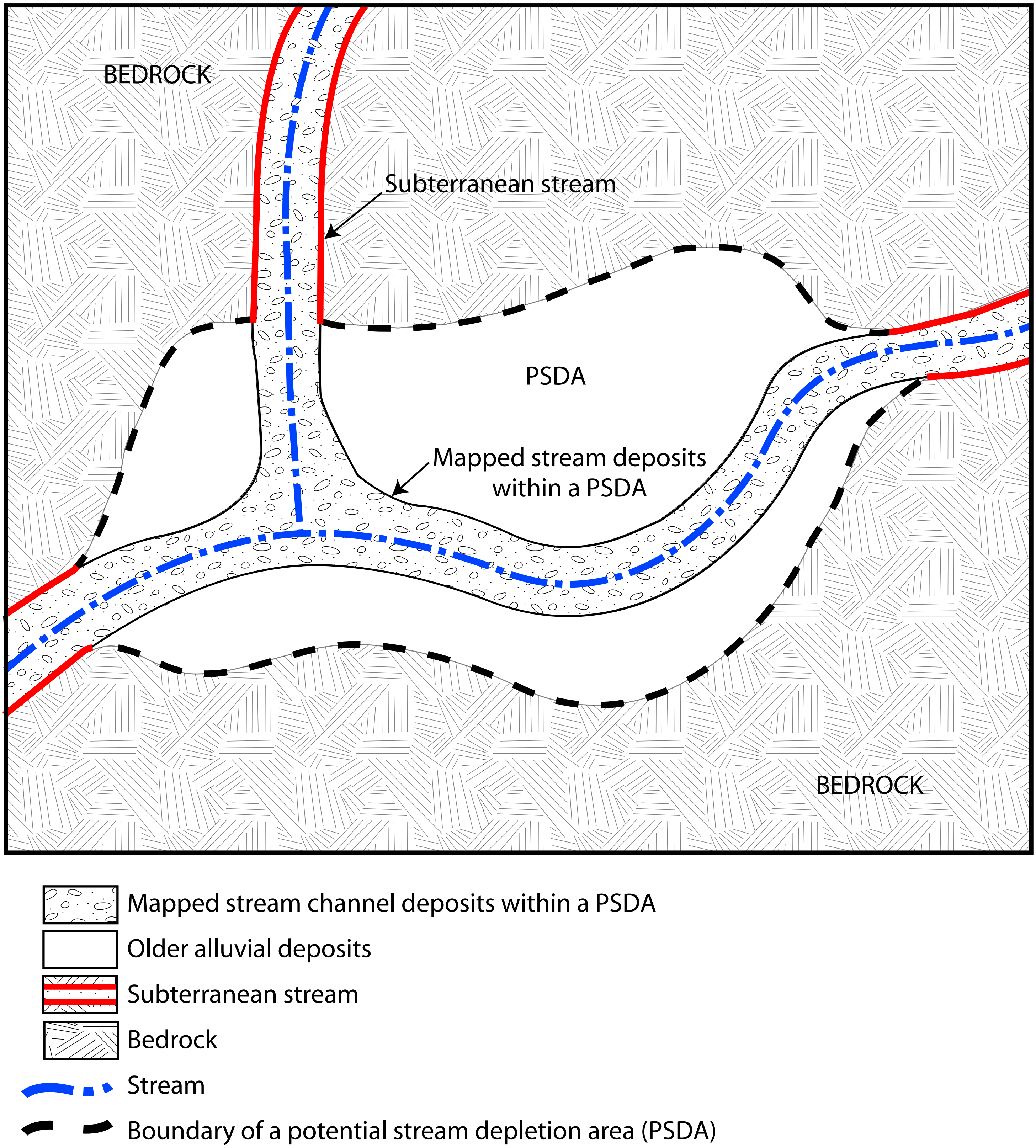
A well does not have the potential to deplete a stream if the well is sealed throughout the alluvial deposits that are in hydraulic connection with the stream and if the well is pumping water from an aquifer that is hydraulically disconnected from the natural channel or subterranean stream.

Methods available for analysis of streamflow depletion include analytical and numerical modeling techniques. The analytical techniques are based upon numerous assumptions. Numerical modeling techniques, which take into account more realistic hydrologic conditions, have advantages over most analytical solutions. However, for numerical models to be superior to analytical models, costly investigations of the hydrology, water use and aquifer characteristics are required. The level and cost of investigations required to develop an effective numerical model(s) for determining stream depletion in the Policy area is not recommended. In the more developed groundwater basins, numerical models may already exist.

A methodology is discussed herein that provides an estimate of potential stream depletion due to pumping from a well located in a PSDA. This methodology is presented in the USGS' *Techniques of Water-Resources Investigations of the United States Geological Survey - Computation of Rate and Volume of Stream Depletion by Wells, Book 4, Chapter D1*, by C.T. Jenkins (1970), an analytical approach referred herein as "Jenkins." Jenkins is most accurate when field conditions approach certain assumed conditions including:

- the stream fully penetrates the aquifer and forms a linear boundary; thus, the effects of stream width and depth, as well as a low-permeability streambed, are not relevant;
- stream stage remains constant in space and time;
- the stream and the aquifer are initially at hydraulic equilibrium; thus, there is no groundwater contribution to stream flow nor does the stream flow contribute to the groundwater;

FIGURE 2



SCHEMATIC MAP SHOWING RELATIONSHIP BETWEEN SUBTERRANEAN STREAMS, POTENTIAL STREAM DEPLETION AREAS AND MAPPED STREAM CHANNEL DEPOSITS

- the aquifer has constant thickness and homogenous hydraulic conductivity in space and time, extends semi-infinitely, and rests on a horizontal, impervious base; and
- the well fully penetrates the aquifer and is pumped at a constant rate.

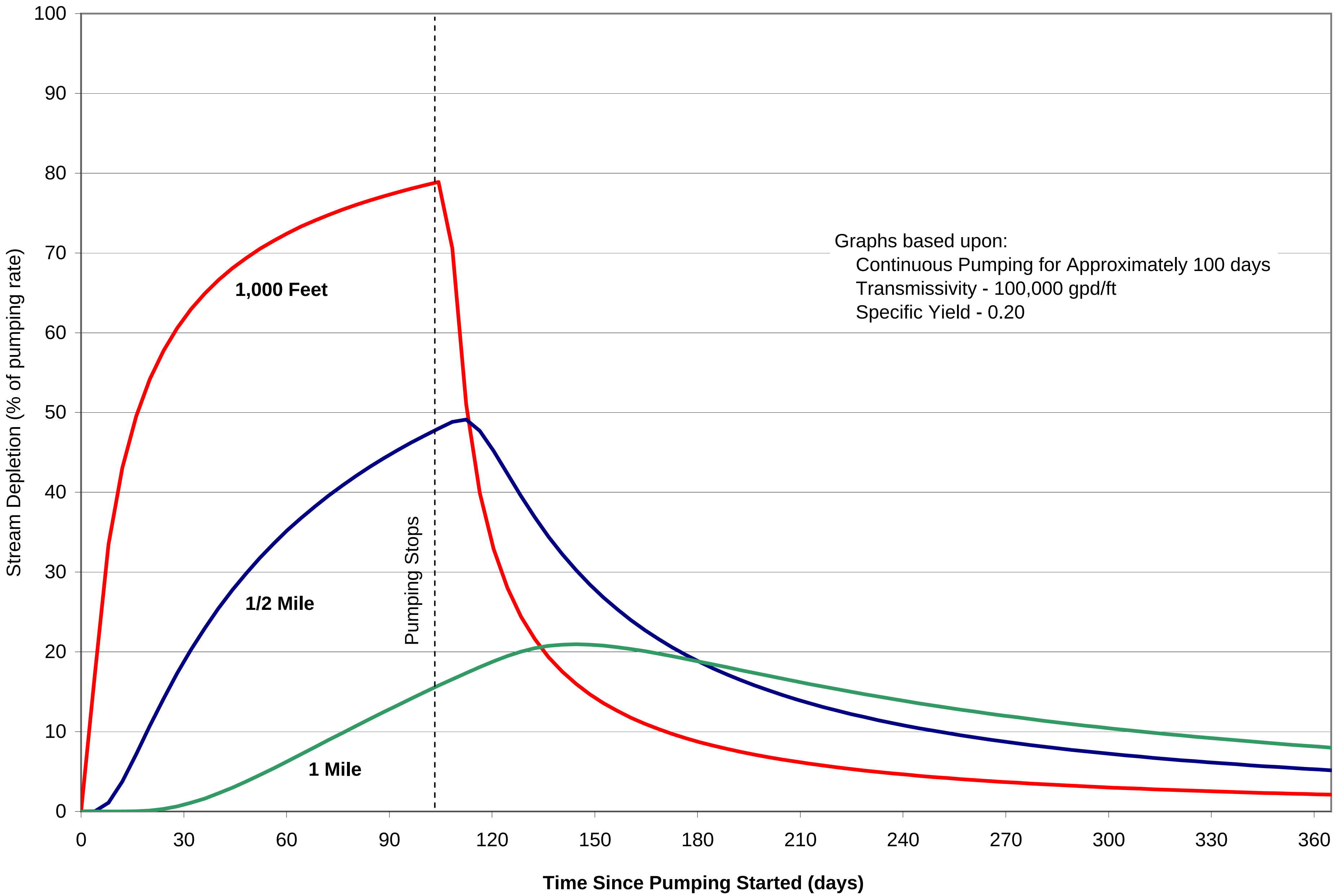
Field conditions do not always meet these assumed conditions, but the Jenkins methodology should be a suitable approach to estimate depletion resulting from a pumped well. The variables that influence the extent of stream depletion include the pumping rate, the duration of pumping, the distance from the well to the stream and aquifer hydraulic properties. However, reasonable assumptions of average values should produce usable results. The significance of these variables relate to the time lag between the start of pumping and the start of stream depletion, the rate of depletion and the extent of continued depletion that occurs after pumping stops. After well pumping ceases, a residual cone of depression exists which diminishes with time. This is reflected by the recovering water levels in the pumped well. A residual gradient toward the well exists as the well recovers. As long as this gradient slopes from the stream towards the well, stream depletion is still occurring. As the distance from the well to the stream increases, the impact from depletion is reduced, but the impact continues for a longer period after pumping has stopped as shown on Figure 3.

Butler, et al. (2001), notes that the Jenkins method over estimates stream depletion when:

- the aquifer is not homogeneous and isotropic and there is vertical movement of groundwater (non-laminar flow). These effects diminish with the distance from the well to the stream;
- the stream bed conductance is lower than the aquifer (which can lead to overestimates of 30 to 60%). As the distance between the well and the stream increases the stream bed conductance becomes less critical and may be negligible for a well located at a distance 200 to 250 times the width of the stream;
- the aquifer system cannot be considered semi-infinite. For most conditions, aquifer width must be on the order of hundreds of stream widths before the assumption of a laterally infinite aquifer is appropriate. A valid solution also depends upon the relative distance of the well to the stream;
- the stream does not fully penetrate the aquifer. It can lead to errors >100% but decreases with the distance from a well to a stream.
- there is recharge other than from the stream;

FIGURE 3

Relationship of the Rate of Stream Depletion
from a Well Pumping to Distance from a Stream



F:\DATA\2172\Task 8.2 Subflow\Analytical Methods\Glover\2172 Russian RV Diversion period Examples V2.xls

- there is a groundwater gradient flowing from the aquifer boundaries toward the stream; and
- the water level in the aquifer falls below the bottom of the stream bed.

The above conditions that can result in over estimates of stream depletion should be considered when the Jenkins method is applied to a specific well, however, they should not preclude the use of Jenkins and other analytical methods in the evaluation of a specific pumping impact on stream flow if other information is used in conjunction with the analytical methods.

The Jenkins solution involves the calculation of a stream depletion factor (*sdf*), dividing it into a specified time of pumping (*t*) and looking up a ratio of the rate of depletion over the pumping rate (*q/Q*) on a chart or table.

$$t/sdf \rightarrow q/Q$$

Where:

t time of continuous pumping

sdf = $a^2 S/T$

a the perpendicular distance from the well to the stream

S the Specific Yield of the aquifer

T the Transmissivity of the aquifer

Q the pumping rate of the well

q the rate of depletion of the stream due to the pumping well

A log-log type curve and/or Table 2 is used to find the value calculated for *q/Qt* for the corresponding value for *t/sdf*.

TABLE 2
VALUES OF q/Q CORRESPONDING TO SELECTED VALUES OF t/sdf

$\frac{t}{sdf}$	$\frac{q}{Q}$		$\frac{t}{sdf}$	$\frac{q}{Q}$		$\frac{t}{sdf}$	$\frac{q}{Q}$		$\frac{t}{sdf}$	$\frac{q}{Q}$
0	0		0.65	0.380		1.6	0.576		5.0	0.752
0.07	0.008		0.70	0.398		1.7	0.588		5.5	0.763
0.10	0.025		0.75	0.414		1.8	0.598		6.0	0.773
0.15	0.068		0.80	0.429		1.9	0.608		7	0.789
0.20	0.114		0.85	0.443		2.0	0.617		8	0.803
0.25	0.157		0.90	0.456		2.2	0.634		9	0.814
0.30	0.197		0.95	0.468		2.4	0.648		10	0.823
0.35	0.232		1.0	0.480		2.6	0.661		15	0.855
0.40	0.264		1.1	0.500		2.8	0.673		20	0.874
0.45	0.292		1.2	0.519		3.0	0.683		30	0.897
0.50	0.317		1.3	0.535		3.5	0.705		50	0.920
0.55	0.340		1.4	0.550		4.0	0.724		100	0.944
0.60	0.361		1.5	0.564		4.5	0.739		600	0.977

This table is reproduced from Jenkins, 1970, page 5. Values are dimensionless.

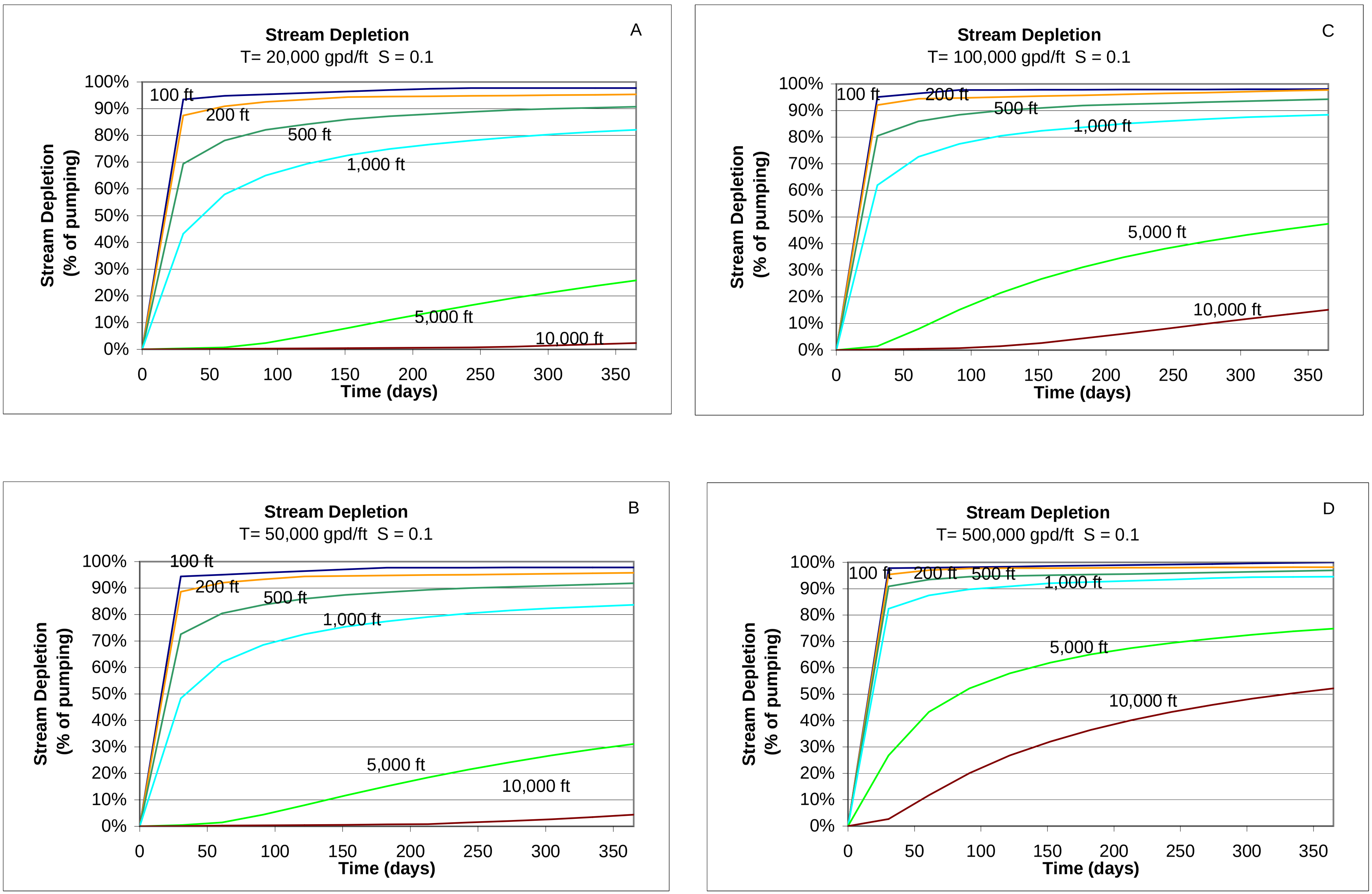
Examples of the theoretical stream depletion using Jenkins for various values of aquifer transmissivity and distances of the pumping well from the stream for specific yields of 0.1 and 0.2 are shown on Figures 4A and 4B, respectively. Stream depletion as represented in Figures 3, 4A and 4B is the percentage of the total volume of water pumped by a well that is theoretically depleted from the stream over a specified time since pumping commenced. For example, a well pumping continuously at 100 gpm for seven (7) days will have pumped about three (3) acre-feet. If stream depletion is indicated to be 50% after seven (7) days, then 1.5 acre-feet is depleted, either directly from surface flow and/or by interception of groundwater moving toward the stream that would have eventually appeared as stream flow.

The graphs shown on Figure 4A and 4B are representative of continuous pumping. The impact on a stream of intermittent pumping is approximately the same as that of steady, continuous pumping of the same volume. All other factors being equal, the impact on a stream is due to the total volume of water pumped, not due to whether a well was pumped continuously or intermittently over a period of time.

The eight (8) sets of curves shown on Figures 4A and 4B indicate that the depletion rate for any specific time is most influenced by the distance of the pumping well from the stream. Transmissivity and specific yield also are significant. The closer the well is to the stream and the higher the transmissivity, the greater the depletion after a period of continuous pumping. Higher values of specific yield reduce the impact on the stream.

Figure 4A

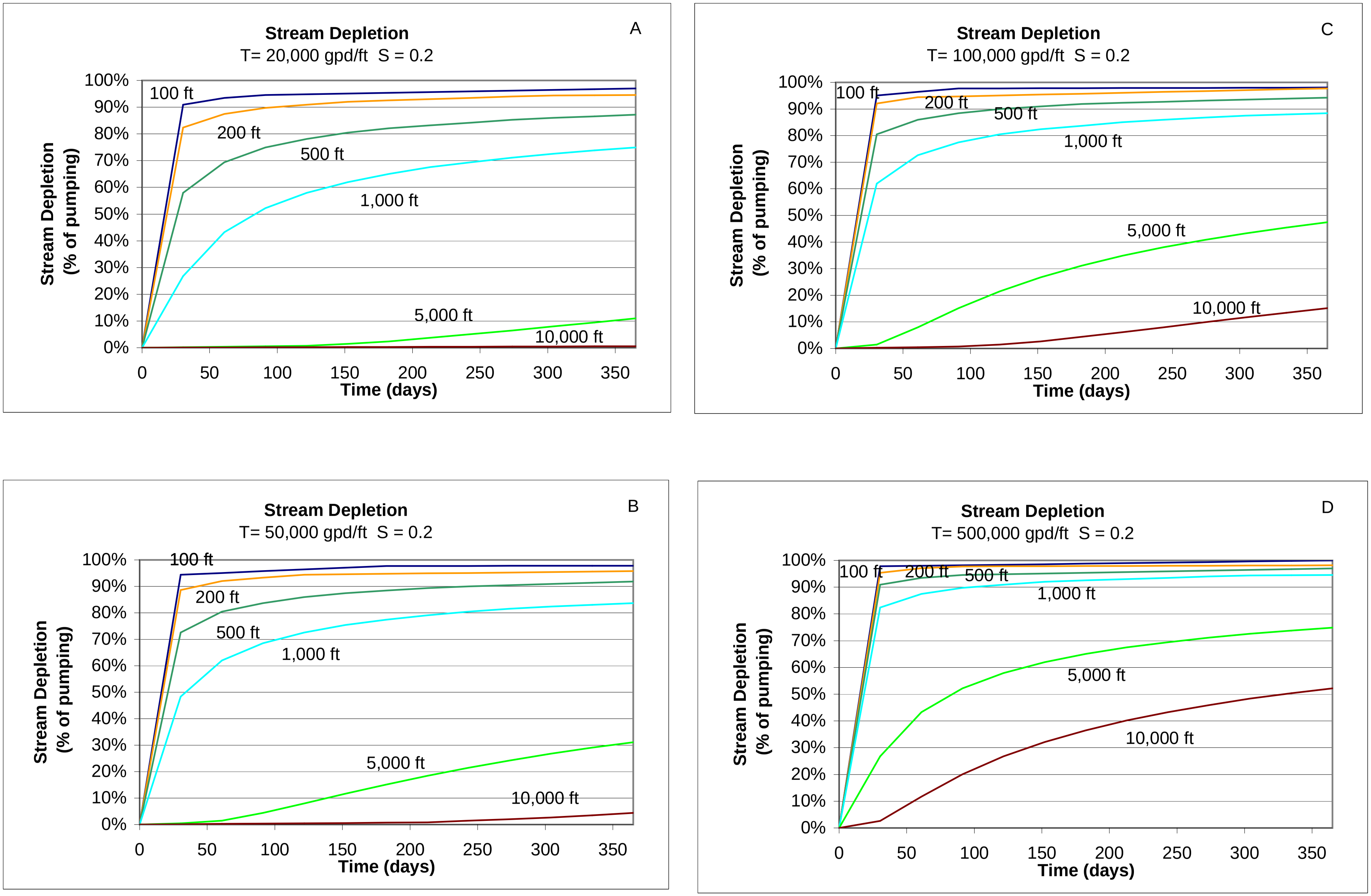
SET 1



Comparison of Theoretical Stream Depletion with Distance of Pumping Well from Stream - Set 1

F:\DATA\2172\Task 8.2 Subflow\Analytical Methods\Jenkins\Stream depletion rate curves Figs 5A & 5B.xls

SET 2



Comparison of Theoretical Stream Depletion with Distance of Pumping Well from Stream - Set 2

F:\DATA\2172\Task 8.2 Subflow\Analytical Methods\Jenkins\Stream depletion rate curves Figs 5A & 5B.xls

Figure 4B

Stream depletion resulting from pumping is not necessarily instantaneous. Some instantaneous or near instantaneous responses (stream flow reduction) can occur from the pumping of wells that are located immediately adjacent to a stream and that are producing water from deposits in hydraulic connection with the stream. Analytical analyses such as Jenkins can only be used as a guide for identifying wells that may be depleting surface water flow. More detailed analysis will be needed to more precisely and conclusively determine the extent of a particular well's depletion of surface flow.

REFERENCES CITED

Butler, J.J., Jr. et al, 2001, Drawdown and stream depletion produced by pumping in the vicinity of a partially penetrating stream: Groundwater, Vol. 39, No. 5., p. 651-659.

California Department of Water Resources (DWR), 2003, California's Groundwater: Bulletin 118, Update 2003.

Jenkins, C.T., 1970, Computation of rate and volume of steam depletion wells: Techniques of Water Resources Investigations of the United States Geological Survey, Book 4, Chapter D1.

APPENDIX A

GEOLOGIC SOURCES

GEOLOGIC SOURCES

Bezore, S., Randolph-Loar, C.E., and Witter, R.C., 2002, Geologic map of the Cuttings Wharf 7.5-minute quadrangle, Napa and Solano counties, California; A digital database: California Geological Survey, Preliminary Geologic Maps, scale 1:24000.

Bezore, S., Randolph-Loar, C.E., and Witter, R.C., 2002, Geologic map of the Petaluma 7.5-minute quadrangle, Sonoma and Marin counties, California; A digital database: California Geological Survey, Preliminary Geologic Maps, scale 1:24000.

Bezore, S.P., Clahan, K.B., Sowers, J.M., and Witter, R.C., 2005, Geologic map of the Yountville 7.5-minute quadrangle, Napa County, California; A digital database: California Geological Survey, Preliminary Geologic Maps, scale 1:24000.

Bezore, S.P., Koehler, R.D., and Witter, R.C., 2003, Geologic map of the Two Rock 7.5-minute quadrangle, Sonoma County, California; A digital database: California Geological Survey, Preliminary Geologic Maps, scale 1:24000.

Bezore, S.P., Sowers, J.M., and Witter, R.C., 2004, Geologic map of the Mt. George 7.5-minute quadrangle, Napa and Solano counties, California; A digital database: California Geological Survey, Preliminary Geologic Maps, scale 1:24000.

Blake, M.C., Graymer, R.W., and Stamski, R.E., 2002, Geologic map and map database of western Sonoma, northernmost Marin, and southernmost Mendocino Counties, California: U.S. Geological Survey, Miscellaneous Field Studies Map MF-2402, scale 1:100000.

Blake, M.C., Graymer, R.W., Jones, D.L., and Soule, Adam, 2000, Geologic map and map database of parts of Marin, San Francisco, Alameda, Contra Costa, and Sonoma counties, California: U.S. Geological Survey, Miscellaneous Field Studies Map MF-2337, scale 1:75000.

California Department of Conservation, California Geological Survey, 2005, Geologic and geomorphic features related to landsliding and landslide potential in the Big River Watershed, Mendocino County, California: Watershed Mapping Series, Map Set 9, scale 1:24000.

California Department of Conservation, California Geological Survey, 2004, Geologic and geomorphic features related to landsliding and landslide potential in the Albion River Watershed, Mendocino County, California: Watershed Mapping Series, Map Set 8, scale 1:24000.

California Department of Conservation, California Geological Survey, 2005, Geologic and geomorphic features related to landsliding and landslide potential in the Elk River Watershed, Humboldt County, California: Watershed Mapping Series, Map Set 4, scale 1:24000.

California Department of Conservation, California Geological Survey, 2002, Geologic and geomorphic features related to landsliding. Gualala River Watershed, Sonoma and Mendocino counties, California. Plate 1, scale 1:24000.

California Department of Conservation, California Geological Survey, 2002, Geologic and geomorphic features related to landsliding. Mattole River Watershed, Humboldt and Mendocino counties, California. Plate 1, scale 1:24000.

California Department of Conservation, Division of Mines and Geology, 1999, North Coast Watershed Mapping, DMG CD 99-002 1999, scale 1:24,000.

Cardwell, G.T., 1958, Geology and ground water in the Santa Rosa and Petaluma Valley areas, Sonoma County, California: U.S. Geological Survey, Water-Supply Paper 1427, scale 1:63360.

Cardwell, G.T., 1965, Geology and ground water in Russian River valley areas and in Round, Laytonville, and Little Lake Valleys, Sonoma and Mendocino counties, California: U.S. Geological Survey, Water-Supply Paper 1548, scale 1:62500.

Clahan, K.B, Wagner, D.L., Bezore, S.P., Sowers, J.M., and Witter, R.C., 2005, Geologic map of the Rutherford 7.5-minute quadrangle, Sonoma and Napa counties, California; A digital database: California Geological Survey, Preliminary Geologic Maps, scale 1:24000.

Clahan, K.B., Bezore, S.P., Koehler, R.D., and Witter, R.C., 2003, Geologic map of the Cotati 7.5-minute quadrangle, Sonoma County, California; A digital database: California Geological Survey, Preliminary Geologic Maps, scale 1:24000.

Clahan, K.B., Wagner, D.L., Saucedo, G.J., Randolph-Loer, C.E., and Sowers, J.M., 2004, Geologic map of the Napa 7.5-minute quadrangle, Napa County, California; A digital database: California Geological Survey, Preliminary Geologic Maps, scale 1:24000.

Clark, J.C. and Brabb, E.E., 1997, Geology of Point Reyes National Seashore and vicinity, California; A digital database: U.S. Geological Survey, Open-File Report OF-97-456, scale 1:48000.

Delattre, M.P., and Sowers, J.M, 2006, Geologic map of the Capell Valley 7.5-minute quadrangle, Napa County, California; A digital database: California Geological Survey, Preliminary Geologic Maps, scale 1:24000.

Graymer, R.W., Brabb, E.E., Jones, D.L., Barnes, J., Nicholson, R.S., and Stamski, R.E., 2007, Geologic map and map database of eastern Sonoma and western Napa counties, California: U.S. Geological Survey, Scientific Investigations Map SIM-2956, scale 1:100000.

Graymer, R.W., Jones, D.L., and Brabb, E.E., 2002, Geologic map and map database of northeastern San Francisco Bay region, California -- most of Solano County and parts of Napa, Marin, Contra Costa, San Joaquin, Sacramento, Yolo, and Sonoma counties: U.S. Geological Survey, Miscellaneous Field Studies Map MF-2403, scale 1:100000.

Jennings, C.W. and Strand, R.G., 1960, Geologic map of California, Ukiah sheet: California Division of Mines and Geology, scale 1:250000.

Koenig, J.B., 1963, Geologic map of California, Santa Rosa sheet: California Division of Mines and Geology, scale 1:250000.

McLaughlin, R.J., Ellen, S.D., Blake, M.C., Jayko, A.S., Irwin, W.P., Aalto, K.R., Carver, G.A., Clarke, S.H., Barnes, J.B., Cecil, J.D., and Cyr, K.A., 2000, Geology of the Cape Mendocino, Eureka, Garberville, and southwestern part of the Hayfork 30 X 60 minute quadrangles and adjacent offshore area, northern California, with digital database: U.S. Geological Survey, Miscellaneous Field Studies Map MF-2336, scale 1:100000.

Rice, S.R., Smith, T.C., Strand, R.G., Wagner, D.L., Randolph-Loar, C.E., Witter, R.C., and Clahan, K.B., 2002, Geologic map of the Novato 7.5-minute quadrangle, Marin and Sonoma counties, California; A digital database: California Geological Survey, Preliminary Geologic Maps, scale 1:24000.

Wagner, D.L., Clahan, K.B., Randolph-Loar, C.E., and Sowers, J.M., 2003, Geologic map of the Sonoma 7.5-minute quadrangle, Sonoma and Napa counties, California; A digital database: California Geological Survey, Preliminary Geologic Maps, scale 1:24000.

Wagner, D.L., Randolph-Loar, C.E., Bezore, S.P., Witter, R.C., and Allen, J., 2002, Geologic map of the Sears Point 7.5-minute quadrangle, Sonoma, Solano, and Napa counties, California; A digital database: California Geological Survey, Preliminary Geologic Maps, scale 1:24000.

Wagner, D.L., Randolph-Loar, C.E., Witter, R.C., and Huffman, M.E., 2003, Geologic map of the Glen Ellen 7.5-minute quadrangle, Sonoma County, California; A digital database: California Geological Survey, Preliminary Geologic Maps, scale 1:24000.

Wagner, D.L., Rice, S.R., Bezore, S., Randolph-Loar, C.E., Allen, J., and Witter, R.C., 2002, Geologic map of the Petaluma River 7.5-minute quadrangle, Marin and Sonoma counties, California; A digital database: California Geological Survey, Preliminary Geologic Maps, scale 1:24000.